JUST-IN-TIME IN HIGH VARIETY / LOW VOLUME MANUFACTURING ENVIRONMENTS

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A thesis submitted in partial fulfilment of the requirements of De Montfort University for the degree of Doctor of Philosophy

October 1995

De Montfort University

ABSTRACT

The implementation of JIT practices within high variety/low volume batch manufacturing environments is currently restricted due to the inability to operate plant layouts that will support the use of kanban material controls.

This research has resulted in the identification of the process sequence cell layout (PSCL) philosophy. PSCL's involve allocating items of equipment to cells according to their position within the operation routing of components. Each cell, therefore, represents a stage in the processing sequence of all components manufactured within a company. Such a layout system enables both material flow to be regulated using kanban controls and the inherent flexibility of functional layouts to be retained.

It has been demonstrated that by adopting PSCL's the benefits of JIT practices may be gained by organisations who produce wide varieties of products/components in small annual volumes using batch manufacturing techniques without the consequent reductions in product and volume flexibility that normally accompanies the use of JIT. An environment is also provided for fast and economical changes to production capacity by altering operator levels within individual process sequence cells and an organisational structure would be provided that favours the use of multi-skilled teams and operator responsibility for quality, machine servicing and lead time reductions.

A PSCL would also provide a means of enabling planning and control activities to be maintained at a local level on the shopfloor. In addition, an environment would be established that both enabled the integration of kanbans and MRP, to be achieved and many of the problems associated with the use of MRP to be avoided. The research performed also describes how the reduction of cell lead times within a PSCL system could be used as the driving force for continuous improvement activities.

Dedication

To Mum and Dad, for all your love, help and support over the years.

Acknowledgments

Many thanks to my friends and colleagues at De Montfort University, especially Colin Haslett, Lee Brown, Stuart Yaxley, Celine Turner and the legendary Mr Sun.

A special thanks to my supervisor Dr. David Stockton for his guidance, patience and relentless cajoling that was necessary to get me through the last three years. Thanks also to Pete Lawrence for his advice.

Thanks also to Rank Taylor Hobson Ltd. for access to their company data and cooperation throughout the project and to Bob Block, production manager at RTH for his personal help.

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List of Abbreviations

The following abbreviations have been used in this text:

ALC	Average-Linkage Clustering
BOM	Bill of Materials
CONWIP	Constant Work-in-Progress
CRP	Capacity Requirements Planning
DCA	Direct Clustering Algorithm
EDI	Electronic Data Interchange
GT	Group Technology
HV/LV	High Variety / Low Volume
LFL	Lot for Lot
LTC	Least Total Cost
LUC	Least Unit Cost
JIT	Just in Time
MRP	Material Requirements Planning
MRPII	Manufacturing Resource Planning
MPS	Master Production Schedule
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
OPT	Optimised Production Technology
PBC	Period Batch Control
PM	Preventive Maintenance
POQ	Period Order Quantity
PSCL	Process Sequence Cell Layout
QC	Quality Circles
ROC	Rank Order Clustering
SCM	Similarity Coefficient Method
SGIA	Small Group Improvement Activities
SLINK	Single-Linkage
SME	Small Manufacturing Enterprise
SMED	Single Minute Exchange of Dies

SPC	Statistical Process Control
TOC	Theory of Constraints
TPM	Total Preventive Maintenance
TQM	Total Quality Management
WIP	Work in Progress

Chapter 1

1. Introduction

1.1 Problems of Batch Manufacturing

The Small Business Administration has defined an organisation as a small manufacturing enterprise, (SME), if it employs between 20 and 1500 people.[1] Using this definition, therefore, approximately 90% of all UK manufacturing companies fall into the category of SME's. Of these businesses around 70% operate a job shop environment and provide goods and services to larger manufacturers.[2] Job shops are characterised by the irregular High Variety / Low Volume (HV/LV) product mix that varies from time period to time period.[3]

HV/LV manufacturing environments generally adopt batch manufacturing as it can be adapted to a wide range of production facilities, and hence product types, and allows economies of scope to be achieved. The importance of batch manufacturing to UK industry cannot be overstated, with the large number of manufacturing firms employing this method of manufacture it is important to understand the characteristics of batch manufacturing and the problems associated with their use. In this respect these are well documented[4,5] with the common problems being identified as difficulties in:

a. achieving short delivery lead times,
b. maintaining reliable delivery dates,
c. maintaining low manufacturing costs, and
d. maintaining reliable quality.

Current market forces demand increased product diversity and are leading to shorter market life cycles for products. These market demands are progressively increasing the proportion of HV/LV manufacturing environments that exist. Hence it is increasingly important to remove these problems.

1.1.1 Delivery Lead Time

Delivery lead times are made up of two basic components, i.e. supplier delivery lead times and in-house manufacturing lead times. In terms of supplier delivery lead times, batch manufacturing organisations normally have to ensure that purchase orders are only placed for the components required to satisfy demand. The component or assembly with the longest supplier lead time dictates the lead time added to the organisations delivery lead time.

In-house manufacturing lead times are normally composed of the following individual task times, i.e.:[6]

a. review and release, i.e. the time taken from receiving a customer order to releasing that order into production,
b. wait or queue, i.e. the time a production job waits after finishing a preceding process before it begins its next process,
c. set-up, i.e. the time taken to adjust or change tooling or equipment prior to processing the next job,
d. processing, i.e. the time taken performing a manufacturing process,
e. teardown, i.e. removing tooling on equipment prior to set-up,
f. move to next facility, i.e. the time taken in handling materials between workstations.

Of these tasks, those that represent the large proportion of the manufacturing lead times are normally queueing times, which are dependent on:

a. the number of processes in the operation route of components,
b. the size of batches to be manufactured, and
c. the order in which batches are to be manufactured.

Manufacturing and supplier lead times have a significant effect on the operational efficiency of an organisation since they:[7]

a. determine the length of the planning and forecasting horizons and hence are directly linked to the accuracy with which data can be obtained and plans can be made, and
b. influence the amounts of raw material, work-in-progress and finished goods inventory that need to be held, hence directly effecting the amount of working capital required by an organisation.

In HV/LV environments, manufacturing and supplier lead times are normally long,[8] hence management are forced to anticipate customer orders using forecasting. Short-term fluctuations in demand are, therefore, difficult to accommodate because materials would already have been part processed when the demand changes occurred.[9] Shorter lead times, however, enable shorter production schedules to be planned which can normally be more readily adapted to accommodate market demand changes, i.e. the response time to order changes is much faster.

1.1.2 Delivery Reliability

Delivery reliability is related to how well a company can predict the actual lead times involved in purchasing raw materials and manufacturing customers orders. In addition, delivery reliability is also related to how well it can maintain those lead times. In batch manufacturing environments both the estimation of individual lead times and maintenance of these lead times is difficult. These difficulties arise due to many factors, including:

a. inability to make use of standard working procedures, that cause variations in set-ups, process and handling times, and
b. inability to effectively plan and control the progress of work through the shopfloor.

1.1.3 Manufacturing Costs

Within batch manufacturing both the direct and indirect costs of manufacturing each unit of product are relatively high when compared with higher volume manufacturing environments. These high costs arise on the whole in the following areas:[10]

a. direct inventory costs,
b. material handling costs,
c. indirect costs of management, supervision, quality control and maintenance,
d. indirect costs of providing production planning, expediting and control, and
e. scrap and rework costs

1.1.4 Quality Reliability

In any organisation poor quality results in wasted effort in rework, wasted marketing and sales effort as well as customer annoyance. The problem of maintaining reliable quality has received much attention in recent years with the increasing use of total quality management (TQM), where quality is inspected at the source of the problem and Kaizen activities that strive to continually improve all aspects of manufacturing. TQM and Kaizen activities, however need to focus in order to identify the problems that will bring about the most significant improvements to the overall system. Batch manufacturing environments do not provide this focus and often disguise the real manufacturing problems.

1.2 Characteristics of Batch Manufacturing

The characteristics of batch manufacture using process layouts have been identified and compared to these of product based layouts by Wild.[11] The characteristics are listed in Table 1, where it can be seen that the layout method adopted has a significant effect on the remaining characteristics of a manufacturing environment. Of particular importance are the planning and control systems adopted since these, in conjunction with layout, have the primary influence on the problems identified previously in Section 1.1.

Table 1 - Comparison of Process and Product Layouts (Wild[11])

Layout by Process	Layout by Product
All similar facilities grouped together	Sequence of facilities derived from needs of product
Low quantity throughput	Large quantity throughput
Large range of items processed	Small range of items processed
Permits specialist supervision	Little specialised supervision required
High work-in-progress	Minimum work-in-progress
High material handling costs	Minimum material handling cost
Ease of provision of services	Difficult to provide services
High space requirements	Minimum space required
Can tolerate breakdowns	Single breakdown stops all machines
Easy to incorporate inspection	Difficult to incorporate inspection
Individual bonus possible	Group bonus
Flexibility, variety and product change possible	Little variety possible
Possibility of loss or neglect of some items	Difficult to lose or neglect items
Maintenance easy	Maintenance out of production hours
Control complex	Control simple
Planning simple	Planning complex
Long throughput time	Low throughput time

1.2.1 Plant Layout

Organisations that manufacture large varieties of components in low annual volumes within a batch manufacturing environment normally adopt functional plant layouts, also called process layouts, because of their inherent flexibility in changing product types quickly and economically. In a functional layout all operations of a similar nature are grouped together in the same department or shopfloor area, which tends to encourage the processing of large batch sizes in order to reduce handling and set-up costs. Large processing batch sizes lead to higher work-in-progress costs and increases in queueing times and hence manufacturing lead-times.

1.2.2 Production Planning and Control

In Table 1 the task of production planning within batch manufacturing environments is identified as 'simple', this is possibly true of planning methods employed, but the use methods does not assist in alleviating the problems listed in Section 1.1.

In recent years has seen the increasing use of computer based planning tools, in particular MRP, MRPII and short term production scheduling packages.[11] These computer based packages have resulted in increases in materials planning efficiency. Within batch manufacturing environments there has been no significant improvement in overcoming such problems as:

1. poor expediting resulting in lost jobs, delayed jobs,
2. changes that occur,
3. breakdowns,
4. lost jobs,
5. lack of visibility of material paths,
6. variety of components,
7. variety of processes and operations, and
8. build-up of WIP.

1.3 Just-in-Time

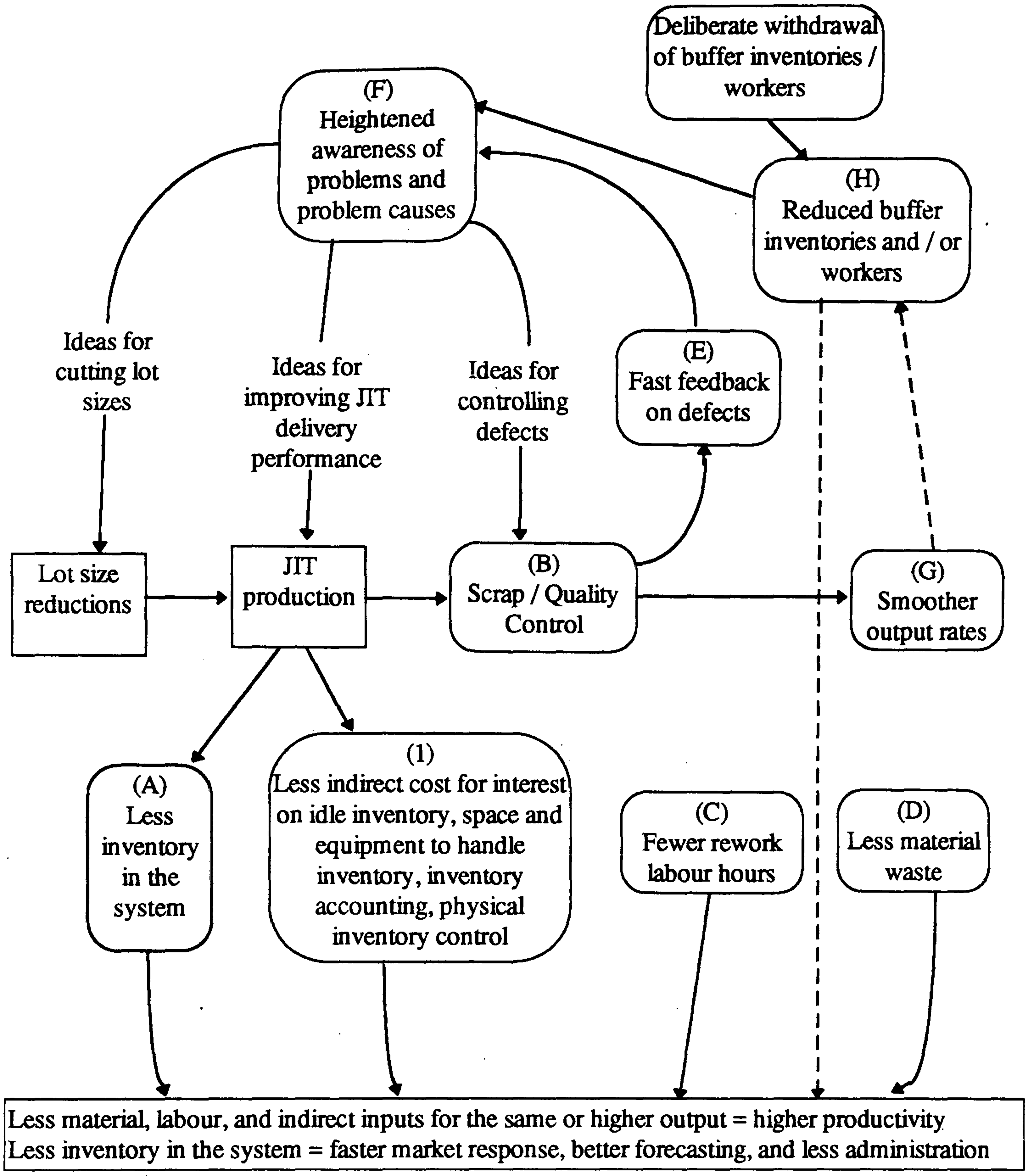
1.3.1 Introduction

Just-in-Time (JIT) has its origins in the shipbuilding industry in Japan and has its rise well documented by Schonberger[12] and Ohno.[13] The JIT philosophy for planning and controlling manufacturing is now recognised and widely used throughout the world.[14] JIT can be defined has a continuous process of using common sense production engineering and management practices to implement practical improvements on the shopfloor. The main benefits to be gained from applying JIT techniques are improvements in those areas that currently pose problems within batch manufacturing environments, i.e.:[15,16]

a. reduced costs of manufacture by providing a focus for continuous improvement, simplification and standardisation of work methods,
b. reduced material handling costs by improving the layout of work areas,
c. reduced inventory costs by providing a focus for set-up reduction exercises that enable reductions in the processing batch size, inter-process re-order levels and work-in-progress levels,
d. reduced inventory costs by reducing the number of components and assemblies stocked by increasing parts standardization,
e. improved delivery reliability through promoting improved work flow rates and providing a focus for improving machine reliability and reducing machine repair times,
f. reduced delivery lead time through providing a focus for the reduction of queueing and set-up times, and
g. improved quality through providing a focus for improving the processing consistency of equipment, operator commitment to quality and control over suppliers quality.

JIT involves changes being made within a manufacturing system by simply forcing a reduction in the amount of inventory that it contains. These reductions are made in steps, each step reduction reveals a set of problems that must be resolved before further inventory reductions can be made. Deliberate removal of buffer inventories in this manner has many effects, as illustrated in Figure 1. In general, lowering inventory levels reduces manufacturing costs and leads to improvements in lead time and delivery reliability. However organisations are forced to implement a culture that can continually overcome the problems that arise when inventory reductions take place.

Figure 1 - Effects of JIT Production (Schonberger[17])



1.3.2 Just-in-Time Tasks

Specific aims have been identified as the main goals of JIT, i.e.:[18]

a. zero defects
b. zero materials handling
c. zero manufacturing lead time
d. zero equipment breakdowns
e. zero set-up time
f. lot size of one
g. zero inventories

Although these aims are idealist in nature, the important concept with respect to them is to adopt a philosophy in which it is important to attempt to achieve them. For example, although it is obviously impossible to reduce lead times to zero, the JIT philosophy states that this goal should be constantly striven towards.

JIT, therefore, is an approach to manufacturing management that demonstrates that companies can effectively reduce lead times and costs while providing acceptable delivery reliability and quality.[19] The operation of JIT is based, according to Bowman[20] and Finch[21], on the following requirements:

a. design products for economical production,
b. change plant layout to facilitate 'flow' manufacturing,
c. institute worker involvement programs,
d. improve data accuracy,
e. reduce paperwork,
f. improve quality,
g. reduce inventories, and
h. strive for continuous improvement in all areas.

Finch, Nelleman and Smith[22] and Basoian and Proud[23] identify additional elements that are necessary for success, i.e.:

a. focused factory,
b. uniform work loads,
c. just-in-time delivery of purchased goods,
d. reduction of set-up times,
e. group technology,
f. total preventive maintenance,
g. kanban, and
h. cross trained employees.

Most of the interest in JIT has been from larger manufacturers, who have adopted these principles and have realised great returns from their efforts. Comparatively little research has gone into the application of JIT to smaller manufacturing companies, who manufacture a high product variety, lower production volumes and rely upon greater flexibility to maintain their competitive place in the market.[24] Its principles are said to apply to any batch type manufacturing operation,[25] regardless of size or type, that produces either work-in-progress or finished products for stock. The applicability of JIT in these conditions is evidenced by the growing number of small enterprises who are adopting these techniques.[26,27]

1.3.3 Current Work

The current work, therefore, seeks to establish the extent to which JIT techniques can be applied within HV/LV manufacturing environments.

Initially the main elements of a JIT environment are examined in detail in order to generate a comprehensive description of the requirements for JIT implementation and operation. These requirements have been grouped into three areas, i.e.:

a. plant layout and kanban controls,

b. planning and control, and
c. JIT infrastructure.

Chapter 2, therefore, examines the principles involved in JIT facilities layout and compares these with the functional layouts used in batch manufacturing. In addition, this chapter also examines the design and operation of kanban controls and other pull system variants.

Chapter 3 examines the manufacturing planning aspects involved in both JIT systems and batch manufacturing environments.

Chapter 4 examines the manufacturing infrastructure required to ensure that the implementation of JIT principles and the process of continuous improvement can be successfully accomplished.

Chapter 5 proposes the adoption of an alternative plant layout methodology, process sequence cell layouts (PSCL's) that have characteristics in common with Druckers[28] concepts of how factories in the future should be designed. He proposed that the future plants will be a 'flotilla', consisting of modules centred around a stage in the production process. PSCL's adopt a similar philosophy in that each cell within the layout is based around a particular stage in the process sequence of components. The chapter then describes how such a layout can be designed and identifies the static design problems associated with such layouts.

Chapter 6 attempts to identify the dynamic design problems involved in the use of PSCL's by the use of computer simulation modeling. A model has been developed that simulates the basic material movements involved in the operation of a PSCL.

Chapter 7 then examines the results of the static design and dynamic design stages in order to identify potential problems when implementing and operating PSCL's. A detailed discussion is then provided on how the problems involved in operation of PSCL's may be solved and how such layouts enable JIT techniques to be implemented.

Chapter 2

2. Plant Layout and Kanban Controls

2.1 Introduction

Essential elements for the successful implementation and operation of a JIT environment are a suitable plant layout and material control using kanban signals. These two elements are instrumental in promoting the benefits of JIT (Section 1.3.1) and focusing continuous improvement activities.

2.2 Plant Layout

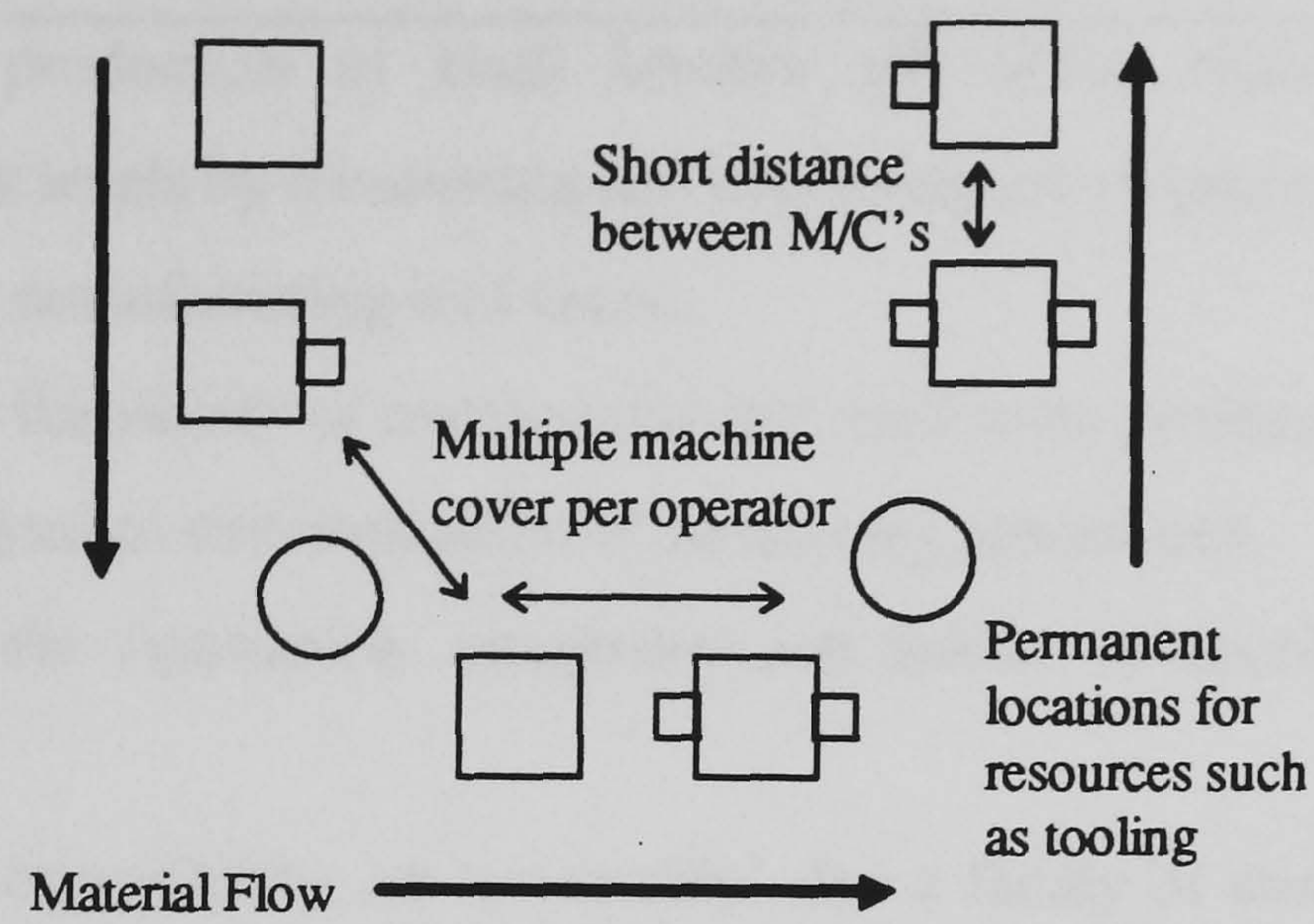
The efficient operation of Just-in-Time requires the adoption of product based plant layouts in which facilities are arranged according to the needs of products and in the same sequence as the operations necessary for manufacture.[29] The layout of machines in this way usually takes the form of either:

a. a production line, in which machines are laid out in a straight line, as often seen in automobile manufacture, or
b. a cell in which machines are contained within a specific area.

In product based cells parts flow directly from one processing machine to the next with the minimum handling distance between movements. The cell area will contain locations for raw materials, work-in-progress, machine tooling and other resources that promote the efficient operation of the machines.[30]

The most advantageous layout of a manufacturing cell has been found to be a 'U' shaped line[31], as illustrated in Figure 2, since this type of layout creates the conditions for supporting JIT, as listed in Table 2.

Figure 2 - U-Shaped Manufacturing Cell



These types of cell layouts minimise material handling requirements, encourage employee flexibility and involvement, provide conditions for multi-functional operators, promote good communications and visibility of products and promote simple visible patterns of material flow through the plant.[32] However, they are unable to operate with large amounts of product variety as cells are designed to cope efficiently only within the conditions for which they were initially designed, i.e. typically a cell would be designed for:[33]

a. stable demand,
b. high and limited range in production volumes,
c. set variability in product mix ratios,
d. limited range of processes,
e. limited range of tooling,
f. limited process route options,
g. continuous production, and
h. single products or a limited range of products that were similar in design, i.e. mixed or multi-model lines.

Table 2 - Cell Support for JIT Production

1.	Allow production of small batches and hence reduce work-in-progress levels by eliminating and improving set-up procedures.
2.	Reduce manufacturing lead times.
3.	Reduce the variety of components that need to be processed.
4.	Allow greater standardisation of processing procedures.
5.	Enable the automation, integration and linking of machines to take place.
6.	Allow responsibility, or 'ownership', for a family of components to rest with one group of operators and their supervisor.
7.	Simplify the planning and control functions by providing conditions for kanban material control systems to operate.
8.	Utilise the flexibility and multiskills of operators due to the machines being closer together. For example, during periods of low demand one employee may be sufficient to operate the cell. As demand then increases, extra employees may be added to ensure that the cell can cope with the extra demand.
9.	Promote teamwork by creating an environment for problem solving, i.e. encourages interest in the work being carried out through ownership. Variety of jobs performed by operator and motivation are enhanced.
10.	Reduce material handling costs, i.e. materials enter and leave cells at roughly the same place allowing individuals to both replenish the cell and remove completed items. In addition, parts requiring rework can easily be moved back into the cell.
11.	Reduce space requirements.
12.	Focus on quality by reducing the time for discovery of faults.
13.	Improve communication.
14.	Allow bottlenecks within a group of machines to be identified more easily.

Product variety limitations are, therefore, built into the system from the initial design. If the requirements of the cell change due to variations in product mix, variations in volume, or introduction of new products, the effects on the operation of the cell can result in poor utilization of some resources, over utilisation of other resources and the inefficient use of cell operators.[34]

In batch manufacturing environments, the traditional method of laying out processing equipment on the shopfloor is in a functional way, as described in Section 1.2.1. These layouts are able to cope with the large fluctuations in customer demand, product variety and product volumes that characterise HV/LV batch manufacturing. In order to form product based facilities layouts within batch manufacturing environments it is normally necessary to reduce the levels of product and/or process variety and increase batch sizes.

In order to reduce variety and increase component volumes, to enable product based flow lines to be economically feasible, Group Technology (GT)[35,36] and cellular manufacture[37] have been developed. These methods have now been widely used to develop product orientated manufacturing cells.[38]

With GT the variety of components manufactured by a company are grouped, where possible, into families on the basis of similarity of design and/or manufacturing attributes, such as:[39]

a. part shapes and sizes,
b. part dimensional tolerances,
c. surface finish requirements,
d. materials used,
e. manufacturing processes or operations required,
f. equipment required to process them, and
g. parts belonging to common assemblies.

When a family group has been identified, the feasibility of developing a small product based flow line for the manufacture of the components within the family is examined. If possible equipment is then laid out according to the needs of the family group and sequential processing and material handling achieved.[40] Hence, parts flow directly from one processing machine to the next with the minimum handling distance between movements.

An alternative method of achieving product based lines is cellular manufacture. This is the technique of laying out a group of work centres that are dedicated to producing a range of products or assemblies. Hence, variety is reduced by separating the manufacturing facilities of individual product or assembly types.

2.2.1 Identifying Group Technology Cells

Early work on the efficient laying out of equipment on the shopfloor, by Hillier,[41] Buffa[42] and Neghabat and Farrokh[43] concentrated upon simply reducing the distances between machines that interact. These methods, therefore, did not arrange processes in the sequence that they were required for particular products and hence failed to provide suitable conditions for JIT, i.e. no visible materials flow.

An approach by Burbidge, production flow analysis,[44] used data from manufacturing routings and was designed for manual calculations, not lending itself readily to computer applications. In a HV/LV batch environment, the high number of parts and consequently routings makes this technique difficult to use and time consuming.

Other approaches to forming groups were developed around machine component group analysis, these methods form groups by manipulating rows and columns of binary information representing the machining requirements of parts.

Complex algorithms have now been developed to identify machine component groups. The Rank Order Clustering (ROC) algorithm developed by King[45,46] considers binary position weights in the machine-component matrix. The machine groups are then identified from diagonal blocks in the modified matrix. The Direct Clustering Algorithm (DCA) developed by Chan and Milner[47] is similar to the ROC algorithm, but ranks rows and columns based upon the position of their non-zero entries. Neither of these clustering algorithms, however, addresses the problems of capacity within a system. Hence these methods may create unbalanced cells in terms of their capacity requirements.

A further approach to machine component group analysis uses a Similarity Coefficient Method (SCM) to form machine groups. The similarity coefficient between two machines is defined as the number of parts visiting both machines divided by the number of parts visiting either of the two machines.[48] Similarity coefficients between machines are entered into a matrix and groups formed again using clustering algorithms. Such algorithms for the SCM method are Single-Linkage (SLINK) and Average-Linkage Clustering (ALC). Other techniques based around SCM that have further improved and extended earlier work have been developed by other authors such as Wagodekar and Sahu,[49] Seifoddini,[50] Askin and Sumbramanian,[51] Kusiak[52] and Charles-Owaba and Lambert.[53]

Later research has identified that the composition of the machine-component matrix is affected by product demand. This later work by Seifoddini[54] has presented a probabilistic demand model to incorporate this aspect of manufacturing. The classification of items in terms of the frequency with which they are manufactured, (i.e. runners, irregular runners and strangers), has also been used to group components.[55] Here a flow line would be considered for those items classified as runners and irregular runners. The removal of 'strange' parts from the design of cells would reduce the problems of machine inefficiency, caused by the inclusion of rarely used equipment for the strange parts. In HV/LV situations a high proportion of the parts to be manufactured would be regarded as strangers, hence making this technique ineffective.

2.2.2 *Limitations of Group Technology and Cellular Manufacture*

Despite improved methods of identifying cells, there are a number of reasons why the traditional approach of identifying and adopting group technology cells is inadequate for many HV/LV organisations, i.e.:[33]

1. Group technology is often not applicable, since it is impossible to identify groups of components from which to form cells.
2. Hybrid systems are often necessary which consist of both GT cells and a functional layout which processes those components not assigned to cells. The advantages to be gained from using flow processing techniques are only achieved on a limited number of part types. In addition, complex production control procedures are still required to manage the functional layout.
3. Cells when formed often cannot fully process all the components assigned to them. Hence components need to leave the cell to be processed then returned to the cell for further processing. The greater the variety of part types within the system the greater is the chance of this occurring.
4. The formation of cells and the assignment of parts to such cells reduces the flexibility of a manufacturing system by restricting such cells to a limited variety of parts and restricting parts to a limited set of process routes. In addition, volume constraints are imposed on the cell making it difficult to either increase or decrease production volumes quickly and economically.
5. The process of preparing numerical codes for components and inputting these into a computer is tedious, error prone, time consuming and costly and often leads to long delays in implementing systems.
6. The variety of part types that need to be processed frequently results in traditional kanbans not being able to cope with such conditions.
7. Once a cell is created it is then committed to making that particular range of parts, making it insensitive to the changing needs of the market.
8. There is often no consideration of the final assembly to which parts belong.

2.3 Kanban Controls

Kanbans, pioneered by Ohno,[13] are essentially visible signals that control the flow of material through a production line. Initially kanbans referred to cards or containers that were used to control material movements by acting as a signal or method of communication from downstream operations that they needed more materials. In this way a kanban system initiates the flow of materials through the shop floor without the need for extensive amounts of paperwork. In addition, they ensure that materials only move at the time they are required, in the right quantities and part types and are moved to the right work centres.

Kanban systems in Just-in-Time environments are 'pull' systems in that the operator signals the upstream process in the cell, thereby 'pulling' the material forward at the rate of use. Demand for a preceding stage's output is generated by the succeeding stage where it is processed. The removal of inventory at the preceding stage authorises the manufacture of an additional unit to replace the one just taken. No manufacturing can occur without such authorisation. As a result, each stage is said to produce just-in-time to meet the demand needed by succeeding stages, which is ultimately controlled by the final product demand at the last manufacturing stage.

Hence, when using kanbans, only the final work station on an assembly line needs to know the end product requirements. With this information this end station can then control, via the use of kanbans, what is produced in the entire manufacturing system. The flow of material can, therefore, be synchronised to the rate at which units of end products are produced.

2.3.1 Kanban Operating Conditions

As with any manufacturing control system the use of kanban cards will only yield satisfactory results under specific conditions, i.e.:[56]

a. when a high level of standard parts and products are being continuously manufactured, i.e. this limits the number of standard containers and cards required by the system and enables the direct transfer of parts between successive work stations to take place,

b. a stable 'Master Production Schedule' for finished products must be established, since fluctuations in demand can only be handled by adding or removing containers and kanban cards,

c. additional involvement is required by workers in handling materials due to the more frequent movement of containers,

d. extensive use must be made of the full range of JIT techniques, otherwise kanbans may not operate efficiently, and

e. when strict operational discipline is maintained at all times in the use of kanban cards. To achieve such discipline requires well documented manufacturing procedures, well trained workers who are well motivated towards following them.

In order to reduce inventory, kanban signals are used as follows:[37,15]

1. Achieve a system that works well with a given number of kanbans then reduce inventory levels by removing a kanban from the system.
2. Solve the problems that arise due to the decrease in inventory.
3. Remove problems until the system is again running smoothly with the reduced number of kanbans.
4. Repeat steps 1 to 3 continuously.

2.3.2 Kanban Types

There are several types of kanban signal, the optimum choice of which depends on operating conditions. Some less well known types of kanban that have evolved include, flag kanbans, verbal kanbans and automatic kanbans. These systems have uses in some environments but in general are prone to failure, either from operator error or in the case of automatic kanbans due to mechanical or electronic failure.[57] The emphasis when using kanbans is on achieving a system that is reliable and allows signals to be visible in spite of the fact that such factors as the shape of the factory floor and the distance between work centres may present problems. The main types of kanban signals to have emerged are:[12]

a. two-bin kanbans which are essentially used for high volume, low cost items,

b. kanban squares,

c. container kanbans, and

d. card kanbans of which there are two basic types, i.e. single card and dual card systems.

2.3.3 Two-Bin Kanbans

Two bin kanbans are the simplest types of system to implement and operate and ensure that shortages of bulk stock never occur.. A two-bin kanban system employs the use of two bins that hold bulk stock, such as nuts, bolts and rivets. Both bins are filled but stock is only removed from Bin 1. When Bin 1 is empty it is taken away for refilling, meanwhile stock is taken from Bin 2. When Bin 1 is returned it is not used until Bin 2 is emptied.

2.3.4 Kanban Squares

A space, typically a square, is marked out on the floor or on a shelf between two successive items of processing equipment and a bin of parts is allocated to this space. Each kanban square can only contain one bin of components, which is identified by the component's code. In addition the square may be marked with the same colour as the tooling required to process the part held in that square. When parts are used, the squares become empty. This is then the instruction for making another bin of the same part type. Kanban square systems are effective in low variety situations and are simple to implement. An increased variety of products results in a need for an increased number of squares and, therefore, high levels of space are required and high levels of inventory occur.

2.3.5 Kanban Containers

In this system a container is designed for an individual part type, such that no other part type may be placed in that container. The signal to make another part is the presence of an empty container, or a certain number of empty containers. The efficiency of the system can be measured by the number of containers in the system. Increased product variety results in increased numbers of containers, and, therefore, high levels of space required, high levels of inventory and high cost of purchasing containers.

2.3.6 Single Card System

In a single card kanban system, the card contains the part name and number of parts to be made. The presence of a card is simply an order to make another batch of these parts. Kanban cards have the advantage when compared with kanban containers in that a particular container is not dedicated to a particular part. Hence savings in both space and containers is obtained. If the operational sequence (Table 3) involved in using a single card kanban is examined it can be seen that increases in product variety will increase the number of different cards required which still leads to in increase in the level of WIP.

Table 3 - Operation of a Single Card Kanban System

1.	Assume a downstream work area has just used the last item in a specific container.
2.	A kanban card is placed into the empty container.
3.	The container is moved to a storage area which could, if convenient, be a central point for all containers, or sited near the upstream work area.
4.	The empty container containing the kanban card is then moved to the downstream work area.
5.	The kanban card is removed and this informs the operator which part type needs to be made and the quantity to produce.
6.	The operator then processes the required parts and places them in the empty container.
7.	When sufficient parts have been produced, (i.e. the quantity on the kanban card and/or sufficient to fill the standard size container), the operator replaces the kanban card in the container.
8.	The full container is then transported to the container storage area where it is then picked up by the operator from the upstream work area.
9.	The cycle of events (a) and (h) repeat themselves once the container has been emptied. Often operators empty containers and transport them back to the central storage area before beginning to process the parts taken out.

2.3.7 Dual Card System

For kanban control in situations where a variety of parts are being manufactured the use of two signals has been developed. Such systems use two cards, i.e. Withdrawal and Production cards, the functions of which are shown in Table 4.

Table 4 - Functions of Two Card Kanban Signals

a.	A **withdrawal kanban** card indicates the quantity of items that subsequent processes should withdraw from an upstream work station. It acts as the authority for a worker to move a container of parts from the output storage area of one work centre to the input storage area of the next work centre.
b.	A **production kanban** card shows a preceding work centre the quantity of a specific item that they should produce. Again it acts as an authorisation, but in this case to signal that parts or sub-assemblies should begin to be processed.

Advanced Japanese kanban users such as Toyota[58] control the stage to stage authorisation of production with such a dual card kanban system. In a dual card system one card, the production kanban, accompanies the containers as they are being produced. When the production of a container is completed and demand for the next stage occurs i.e. as indicated by the withdrawal kanban card from that stage, the kanban is removed from that container and is returned to the production ordering kanban post at the same stage. The withdrawal kanban from the next stage actually replaces the production kanban on that container, and accompanies the container to the next stage.

For production activity to take place at a stage, both a production kanban card and a container of the required parts, accompanied by a withdrawal kanban card, must be present at that stage. When the production process begins, the withdrawal kanban of the required parts is sent back to the preceding stage where it authorises that stage to produce the container of parts now required at the next stage. This creates a continuous cycle of container movement between stages of the production process.

Two kanban card exchanges are therefore made; one immediately prior to the production activity and one immediately following the production activity at each stage. The production kanban remains at its 'home' stage whilst the withdrawal kanban moves between stages. Hence the production kanban acts as an intraprocess controller and the withdrawal kanban acts as an interprocess controller. The operator can identify which job to process next as the cards available for processing are hung from a 'scheduling board', i.e. the next job is indicated by the position of cards on the board.

The number of kanban cards for a particular part and an example of production and withdrawal kanban cards are illustrated in Figure 3. It can be seen that the number of kanban cards required in the system will depend on the variety of both the part types processed and the type of processes used.[59,60]

Figure 3 - Kanban Cards and Card Quantity Calculation

Withdrawal / C- kanban

Item number:	Preceding process:	
Item name:	Subsequent process:	
Container type:	Date issued:	Container capacity 1

kanban card number

Production kanban

Item number:	Process:
Item name:	Quatity 1

Let, Y = number of kanbans
D = usage rate planned for the part (units/day)
Tw = average waiting time for kanban
Tp = average processing time
a = container quantity (not more than 10 % daily required)
v = policy variable (not more than 10 %)

Then:

$$\boxed{Y = \frac{D\,(Tw + Tp)\,(1 + v)}{a}}$$

2.3.8 Kanban System Benefits

The JIT philosophy implemented through the use of kanbans has been shown to produce significant savings by reducing inventory levels, i.e. pull systems enable queues, inventories, and stocks to be held at a minimum.[61] In addition, other benefits of using kanban signals are:[62]

a. no expediting is required between the stages of production, i.e. the need for shopfloor control and production schedules is avoided,
b. kanban makes full use of workers capabilities,
c. efficiency can be improved by exposing problems with the removal of individual kanban signals, i.e. improvements can be forced by the removal of cards from the system,
d. excess work-in-progress is avoided because the use of standard containers makes the build-up of inventory highly visible,
e. restricting the number of containers or sites where containers may be stored provides a physical limitation to the build-up of excess inventory,
f. empty containers present at a machine act as a visible signal to operators and supervisors that there could be a problem at an upstream work station,
g. removing some of the available containers from the system physically prevents the production of work-in-progress,
h. increases throughput rates on the shopfloor by reducing inventory,
i. creates self regulating material flows that rely on visible control signals,
j. the information flow is closely linked to the material flow,
k. deliveries of raw materials from suppliers can be linked to the kanban system to take place on the shop floor again promoting a smooth flow of materials,
l. involvement of operators to achieve high productivity levels, and
m. most special design goods can be designed to be made from standard materials and components that can be ordered, delivered and produced using kanban containers and cards.

2.3.9 Kanban System Limitations

In a HV/LV manufacturing environment there would be a need for a high number of kanban cards or containers and a corresponding increase in the level of WIP in these environments. Kanban systems also have other limitations, i.e.:

a. kanban is a very rigid system, as Chaudhury and Winston comment, "there is nothing in the kanban system to explore the extra dimensions of flexibility",[63]
b. kanban is not suitable for production of specially designed goods unless ordered in large volumes,
c. the implementation of simple kanbans neglect the need for engineering changes to take place, and
d. if defective items were produced disruptions to subsequent processing operations would take place.

2.4 'Pull' System Variants

2.4.1 CONWIP

Pull type systems that have been used in non-repetitive manufacturing environments generally adopt elements of MRP and kanban.[64,65] One such system developed by Spearman et al[66] is the CONWIP (CONstant Work In Progress) system and is applicable to systems that have a higher variety of products. As with kanbans, CONWIP assumes that parts are moved in standard containers, all of which contain approximately the same amount of work. CONWIP relies on signals, usually cards, to control the system. The cards are attached to the standard containers and traverse the entire production line with the container. The cards then return to a card queue at the beginning of the line and wait there until being attached to another container.

CONWIP differs in its use of cards from traditional kanban systems in that they are not component specific. Component numbers are assigned to the cards at the beginning of the line and are matched together by referencing a backlog list. The first component number on the list is the first one that should enter the system. The time the part enters the system is also be noted on the card. The backlog list is maintained by the production control staff and should be produced from the master production schedule of the MRP system. No production can be started without a card present even if the first process is idle.

2.4.2 Periodic Pull System

A periodic pull system is a computerised material management system that, at regular intervals, reviews the status of material flow at all processing stages, termed review periods. As a result of a review, only the exact amount of material that has been consumed at a succeeding stage since the last review time is allowed to be withdrawn from or produced at a preceding stage.[67] The withdrawal and production operations begin immediately after a review has been performed.

2.4.3 Period Batch Control

Period Batch Control (PBC)[68] is a single cycle ordering system in which orders are issued at a series of regular intervals for completion by a complementary series of due dates, conditioned by the complexity of the components to be manufactured.[69] The advantages of PBC when used in conjunction with GT are that:

a. an even load of work is provided to each cell since PBC is a single cycle system,
b. parts are made in small batches, hence stock levels are reduced,
c. set-up times are reduced since ordering in period sets makes 'sequencing' in tooling families possible,
d. stock holding costs are reduced, because there is less stock, and
e. operation scheduling is simplified, i.e. there is one common due date, there are accurate period load figures, and low numbers of machines and parts within each group.

2.4.4 Push Kanbans

Push kanbans are essentially an enhanced MRP system in which daily capacity requirements planning can be carried out for individual work centres within a cell such that work loads are balanced within manufacturing areas.[70] Each job has a coloured card, with scheduling boards to prioritise jobs.[71] The floor area in front of individual items of processing equipment is marked to indicate the space for two incoming and two outgoing batches, these areas act as 'regulators',[72] where materials are staged through rather than stored in them. This system acts as a 'push kanban', i.e. materials are pushed into the incoming area which can only contain a limited number of jobs hence providing a physical constraint to work-in-progress levels.[73]

2.4.5 Buffer Management

Buffer management is a control mechanism which has been developed with the introduction of the theory of constraints discussed in Chapter 3. Buffer management has been developed to deal with the scheduling complexity of job shops by focusing attention only on critical resources. Gardiner et al state that buffer management:[74]

a. provides a framework that reduces the complexities of material flow into an understandable format,
b. reduces drastically the number of resources that must be explicitly scheduled,
c. warns of potential disruption to the production plan,
d. controls lead time,
e. guides continuous improvement methods,
f. offers a significantly improved alternative to the kanban production system,
g. aligns local resource performance measures with organisationai performance, and
h. makes traditional job shop capacity management techniques obsolete.

2.4.6 Kitting

Kitting requires that the components that make up a final product or assembly be collected together into an appropriate container, in order to reduce material handling at later stages in production. Ding and Puvitharan state that a successful kitting system should:[75]

a. eliminate search time as all needed parts are in a single kit,
b. improve control over WIP,
c. improve shop floor control, and

d. reduce material handling by sending a kit of parts rather than individual parts to processing stations.

Kitting becomes appropriate and beneficial when applied to assembly in the electronics industry[76] and can also operate successfully within a JIT environment, i.e. part kits are pulled through the shopfloor in response to kanban cards,[75] However the costs associated with kitting due to accurate picking can be high due to the direct labour requirements.[77]

2.5 Lean Production

The aim of lean production are directed at introducing JIT techniques in small well defined production areas in short periods of time, typically less than one week. Lean production aims to:

a. reduce cycle time by eliminating non-value added time,
b. ensure that materials can move in a smooth continuous flow by reducing batch sizes and changing the layout of processing equipment,
c. eliminate all forms of waste, i.e. processing waste, inventory, over production, scrap, rework and materials handling waste, and
d. use a highly skilled workforce that can assist in maintaining and improving the manufacturing system by finding and correcting problems and causes of defects.

A typical implementation, i.e. termed a lean production workout, would involve all activities taking place on the shopfloor in the area being examined using on a full time basis, a multi-skilled team, as follows:

1. Identify a small number of products that represented all the work performed in the manufacturing area.
2. Obtain the sequence of operations required to manufacture the representative parts.
3. Identify the key manufacturing information for each of these processing operations, this is termed 'process mapping'. Here it is important that the information is gathered quickly by people involved in the

4. Improve the individual methods used to process parts by eliminating, combining or re-ordering individual operations.
5. Calculate the TAKT time, this is the frequency with which items must be fully processed in order to meet customer order requirements.
6. Determine the minimum batch size and the batch cycle time that can under current set-up conditions be processed.
7. Identify the bottleneck process that requires set-ups, this is normally the process that either possesses the longest processing time or possesses the longest waiting time before work can be processed on it, or has the longest queues waiting to be processed.
8. Calculate the amount of time that is available for setting-up the bottleneck machine.
9. Calculate the minimum batch size that can be processed and the batch cycle time.
10. Allocate operations to work stations, such that any one work station does not have more work allocated to it then the batch cycle time.
11. Calculate the minimum number of operators required in the new layout.
12. Rearrange equipment into a product orientated cellular flow line.
13. Identify and correct concerns, i.e. problems that prevent efficient operation such as work area times greater or less then the TAKT time.
14. Establish leveled repetitive schedules.
15. Implement a system of continuous improvement in order to remove the remaining causes of concern.

Chapter 3

3. Manufacturing Planning

3.1 Introduction

Initially planning within JIT environments follows a similar sequence to that of non-JIT manufacturing systems. Long term strategic plans are made and then converted into operational objectives ideally using aggregate planning.[78]

The planning horizon for the aggregate plan is normally a year in order that there is sufficient time available to implement suitable capacity adjustment methods. Labour requirements and capacity needs of product families are determined for each month of the aggregate plan. In a JIT environment the aggregate plan can be used to design and develop cells or production lines. However, in a HV/LV environment the aggregate plan often only serves as a guide to making capacity changes.[79]

The next stage in the planning cycle involves the development of the Master Production Schedule (MPS). This schedule lists the quantities of end items and product options that need to be produced during specific weeks. The MPS quantities may be derived from both forecasts of demand and actual sales orders. The planning horizon adopted for the MPS is dependent on the manufacturing lead times for a particular organisation.[80]

When lead times are long then organisations may be forced to use demand forecasts to derive their MPS quantities. Whereas, when lead times are short it may be possible to use actual customer orders hence providing more accurate data for planning purposes. When MPS lead times are long, uncertainty is introduced into the system brought about by, changes in suppliers, long term machine breakdowns or changes in the workforce.[79] The MPS is normally frozen for one month in advance and tentative plans are produced for the following two months. A JIT environment demands that little change occurs in demand between MPS periods.[24] However, this would normally not be possible in a HV/LV environment.

Within a JIT environment the MPS can be used to prepare weekly final assembly schedules for production lines. These schedules indicate the number of individual parts that need to be produced on a daily basis. Ideally this assembly schedule should, if possible, be 'leveled'. Leveling ensures that minimum quantities of each product type are in production simultaneously and daily production of each product type meets the MPS requirements. However, this requires stable demand and leveling becomes more difficult as product variety increases.[81]

Within both JIT and batch manufacturing environments the next stage in the planning process is material requirements planning (MRP), which is used to identify the requirements for the purchased components, that are needed to meet the MPS. In addition, within batch manufacturing environments MRP also determines the materials that need to be made in-house.[80]

If variety exists then within a JIT environment the final stage in the planning procedure is to determine the sequence with which product types will be launched or produced on the production line. It is the success of this procedure that enables a single production line to economically manufacture a variety of products in a single day, i.e. mixed-model mode. Mixed-model sequencing allows individual products to be manufactured in short lead times and hence enables an organisation to cope with short-term variations in market demand. The objective of mixed-model sequencing is to determine the order in which product types should be produced such that:[78]

a. production of each product type is evenly spread throughout the day,
b. a set sequence can be identified that allows materials to flow smoothly down, the production line, i.e. this sequence, if possible, must be repeated during the day and over a number of days until demand changes,
c. each product's daily requirements are produced each day,
d. the workload is distributed evenly at each work station, and
e. excessive problems with changeovers are not experienced.

If any appreciable variation in demand or product mix occurs then the efficiency with which line sequencing can be performed quickly falls. Within a batch manufacturing environment the final planning task is production scheduling. Production scheduling is the process of deciding which products are processed on which machines and in what order. This is essentially a decision making process in that it requires specific information in order to achieve an optimum solution to the scheduling problem, i.e. the information required includes:[79]

a. knowledge of what jobs need to be included in a schedule,
b. knowledge of the criteria to be used to select an optimum schedule, i.e. relevant criteria are often difficult to identify or may change over time, and
c. knowledge of the relative importance of the above criteria to the decision process, i.e. the relative importance of individual criteria may change in time.

3.2 Material Requirements Planning

The MRP process identifies the orders that must be placed on both the manufacturing facilities and suppliers for the assemblies, components and raw materials that are needed to assemble the quantities of finished products listed on the MPS. The MRP process also identifies the time at which material orders should be placed with suppliers or on the shopfloor such that finished goods stock can be made available on the dates requested by the MPS. MRP is, therefore, used to generate order schedules for the replenishment of made-in and purchased items and raw materials. The variety present in products, batch sizes, lead times and set-up times makes the use of MRP essential in a high variety/low volume manufacturing environment. Even in some JIT environments where complex product designs are being manufactured, such as domestic appliances, and automobiles, MRP is used to determine order schedules for suppliers, particularly with respect to those that possess long purchase order lead times.[64] However, within such environments actual deliveries are then often controlled using such techniques as kanban signals, faxbans, EDI[82] and links between the customer/supplier stock files.[83]

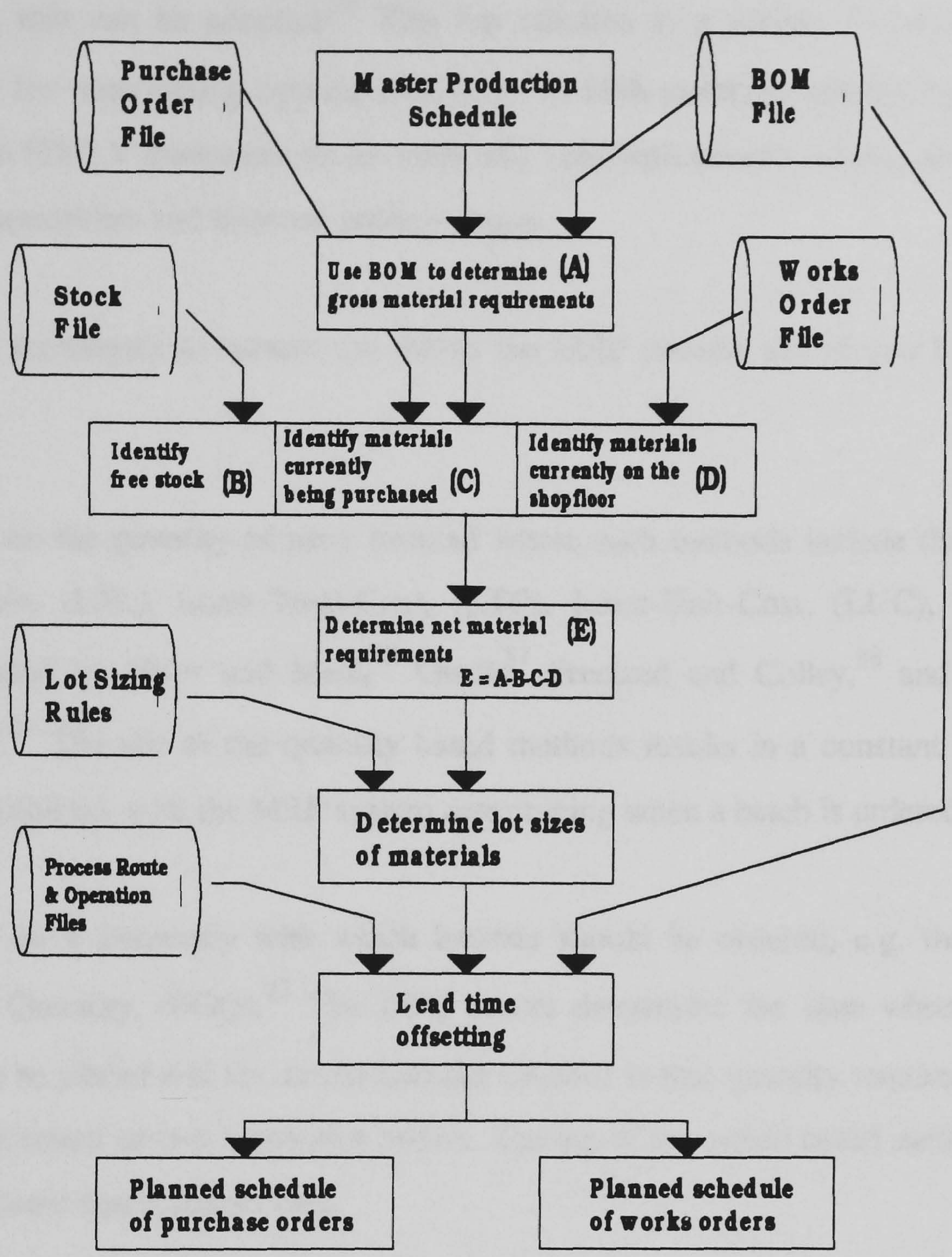
3.2.1 Need for MRP

The basic logic involved in the MRP process is shown in Figure 4. MRP is essential within HV/LV environments since variety and change exist throughout the manufacturing system and all stages of the MRP process are affected by this variety as shown in Table 5.

Table 5 - Variability within the MRP Logic[11]

Variability in the MPS	Occurs from inaccurate demand forecasts, customer order changes.
Variability in product mix	Occurs from job priorities changing, routed products from equipment breakdowns or rework.
Variability in stock quantities	Occurs from multi-sourcing, changes in prices, storage space, concession stock, JIT suppliers.
Variability in suppliers	Occurs from changes in price, changes in quality, change in available storage space.
Variability in works orders	Occurs from rework problems, changes in product mix.
Variability in process routes	Occurs from equipment breakdowns, preventive maintenance procedures, labour changes.
Variability in materials	Occurs from product redesign, changes in supplier materials.
Variability in demand dependency	Occurs from product redesign, material shortages.
Variability in lead times	Occurs from changes in scheduling priorities, machine down times, re-routings.
Variability in batch sizes	Occurs from changes in MPS, customer orders, change in set-up procedures.

Figure 4 - Basic MRP Logic[84]



3.2.2 Lot Sizing

The approach to lot sizing within JIT and batch manufacturing differs. Within JIT systems the philosophy adopted is to minimise lot sizes and to use reductions in lot sizes to drive the process of continuous improvement. Lot size is, therefore, determined such that there is sufficient time for changeovers to take place and still provide sufficient processing time.[85] Kanban controls are used to control batch sizes and ensure that common lot sizes exist between processes. When JIT systems are first implemented safety stock are often incorporated, i.e. these 'safety margins' usually take the form of extra kanban containers or cards allowing additional stock into the system.

Within batch manufacturing environments, however, many factors effect the optimum batch size that can be adopted.[84] This has resulted in a variety of methods being developed for determining optimum lot sizes to both purchase and manufacture. In addition, in HV/LV environments lot sizes may vary both between components used in common assemblies and between process stages.

Lot sizing techniques in current use within the MRP process are of two basic types, i.e.:

a. Based on the quantity of parts ordered where such methods include the Lot-For-Lot rule, (LFL), Least-Total-Cost, (LTC), Least-Unit-Cost, (LUC), and those developed by Silver and Meal,[86] Groff,[87] Freeland and Colley,[88] and Bahl and Zionts.[89] The use of the quantity based methods results in a constant batch size being ordered, with the MRP system determining when a batch is ordered.

b. Based on a frequency with which batches should be ordered, e.g. the Periodic Order Quantity, (POQ).[79] The POQ model determines the time when an order should be placed and the actual quantity ordered is that quantity required between the placement of two successive orders. The use of the period based methods allow the ordered batch size to vary.

The lot sizing logic underlying the MRP process can have a profound effect on the profitability of an organisation. In this respect the lot sizes chosen for the highest level components determine the quantities of lower level items required. Hence complex demand relationships can often exist between such items.

As described above there are a variety of lot sizing methods available and choosing which technique to use from the wide variety available is a major problem since each technique will only yield acceptable results under a limited range of demand and inventory cost conditions.

3.2.3 *Limitations of Existing Lot Sizing Methods*

A critical appraisal was carried out by St. John who highlighted major misconceptions in the evaluation of existing MRP lot sizing techniques. He argued that the majority of the current methods in use are not applicable to MRP since:[90]

1. They treat the lot sizing problem as a single stage process, i.e. determine lot sizes for single items. MRP is, however, a multi-stage process and any lot sizing techniques must take into consideration the relationships between items.
2. Each individual technique is valid, i.e. produces acceptable order schedules, under a particular set of conditions. The effectiveness of a technique for example is strongly dependent on such factors as the variability in the sizes of individual material requirements, the variability in the frequency of requirements, and the relative values of carrying and purchasing costs. In order to achieve good results, therefore, it is necessary to select with care the most appropriate method from amongst the many available. Choosing a specific lot sizing method for each item/demand period is again clearly impractical since regular checks would, therefore, need to be carried out to ensure that changes had not occurred that adversely effected the suitability of the technique being used.
3. All existing methods use costs to measure how effective a specific lot sizing policy is. It is uncommon, when determining lot sizes, for non-cost variables such as the availability of working capital for purchasing stock or warehouse space to be considered. Hence situations can occur in which there is insufficient working capital or storage space to support the purchasing decisions made by a MRP system.

3.3 Lead Time Phasing

Lead time phasing is a technique that identifies the time when a works order should be released onto the shopfloor in order that it can be processed just before the due date, hence minimising the time that WIP is held within the system. In order to take this into consideration, time phased scheduling of orders is performed by MRP to allow adequate time for purchasing and production and to reduce the pre-processing storage time. However, this can be a source of error in batch manufacturing which the use of JIT helps remove through backflushing.[91]

3.3.1 Purchase Lead Times - JIT

Within a JIT environment the problem of variable purchase lead times does not arise since suppliers are given firm long term orders and short term delivery schedules. The emphasis on choosing suppliers in terms of their delivery reliability, use of penalty clauses and the greater purchasing power due to the large order sizes assists in ensuring that shortages of components do not occur.

3.3.2 Purchase Lead Times - Batch Manufacturing

In batch manufacturing environments although delivery lead times are normally specified on the purchase order contract they can in practice be variable. This is particularly true if supplier choice is based on price rather then on delivery and quality reliability. Hence, there is a need to monitor the state of purchase orders at suppliers to ensure that late deliveries do not arise. The MRP system assists in this area by providing exception reports that highlight all late or potentially late orders. In terms of quality reliability, the arrival of defective items cannot be foreseen, but when it arises results in increased delivery lead times, i.e. until replacement parts arrive.

3.3.3 Processing Lead Times - JIT

JIT product based flow lines normally consist of a number of separate work stations each of which is assigned a common cycle time. This cycle time determines the rate at which work flows from one work station to the next. Processes are carried out simultaneously hence the concept of lead time is not appropriate to this type of manufacturing system. In multi-product JIT systems there exists WIP between work stations to ensure that when a particular product type needs pulling through the system there is material available for each work station to process. This ensures that customer delivery lead times are minimised and equipment utilisation is maximised.

3.3.4 Processing Lead Times - Batch Manufacturing

It has been stated in Section 1.1.1 that in batch manufacturing environments queueing time normally constitutes the larger proportion of the total processing lead time. The actual queue time for a specific job is dependent on such factors as current work loads awaiting processing, machine breakdown and repair patterns and the amount of WIP on the shop floor. The effect of such factors varies with time, due to changes in demand levels, and hence queueing times are difficult to accurately estimate. The batch size used in batch manufacturing also has an effect upon the lead times, especially when large set-up times are involved.

3.3.5 MRP Data Outputs

Table 6 indicates that besides planning information for works and purchase ordering, the MRP process provides essential information for other planning functions.[92] In particular the information required to perform Capacity Requirements Planning (CRP) is essential within a HV/LV environment where capacity demands on individual work centres may need to be planned on a daily basis.

Table 6 - MPS Planning Information

a.	Identifies the changes to order due dates and quantities that need to be made to the MPS in order that it may become feasible.
b.	Provides answers to 'what if' questions, e.g. what would be the result to the MPS if an additional order was added or the delivery date or an existing order brought forward.
c.	Provides the MPS planners with information about production or material supply problems that would result in changes to the MPS being necessary.
d.	Provides the CRP process with shop floor order details, (e.g. item codes, quantities, start date for processing), from which capacity load profiles can be established for each work centre.
e.	Provides information that allows shop floor facilities to be efficiently planned and processing delays or capacity shortages identified.

3.4 Limitations of MRP Systems

Implementing and using MRP systems requires management commitment and the provision of an environment that supports the use of MRP, the successful implementation of a MRP system requires a behavioral change on the part of the workforce. In this respect it is necessary to ensure that organisations use MRP systems that are technically capable, ensure accuracy of data inputs and employ disciplined working procedures. In addition, employers need to be educated in the use of MRP through the use of training programs that provide both understanding of the principles behind MRP and the detailed working procedures required for its use, all of which are expensive and time consuming. Continual monitoring must also be employed to ensure that expected results are achieved and that improvements in inventory levels, manufacturing productivity and cost reductions are actually obtained. Methods need to be found to correct any cause of problems within the MRP environment.

Within batch manufacturing the implementation and use of MRP packages have proved disappointing to many organisations when, through lack of experience and education, they have failed to achieve expected benefits. In this respect many of the problems associated with the successful introduction of MRP systems within industry are related to the level of accuracy with which data is maintained. Hence, the need for rigid working procedures which must be implemented to ensure that any event that MRP should be aware of is input into the computer accurately and in good time.[93] In addition, accurate and up-to-date records must be maintained in the BOM and inventory status files and estimates must be made of MPS order quantities and manufacturing lead times, bar coding applications may aid in speeding up this procedure.[94] In this respect, lead times are considered variable[95] and efforts made to minimise such times. For example, controlling the levels of WIP on the shop floor or the amount of work awaiting processing at bottleneck workcentres avoids increases in overall queueing times. When mistakes are made in lead time calculation then monitoring orders at all stages of the purchase and manufacturing cycle is necessary, in order to provide information that can be used to modify production schedules when planned lead times are in danger of being exceeded. If changes do occur then actual lead time information should be used to update MRP output and hence re-plan those jobs affected by these changes.

When choosing a MRP system it is important to ensure that the system selected is technically capable of coping with the frequency of both planned and unplanned events. Here, unplanned events are those that do not occur when or how expected, for example, too few parts may be produced due to defective raw materials being used or parts may be made ahead of time. Common unplanned events include changes to master production schedule times and quantities, changes in BOM structures and sales orders received/dispatched. Each time an unplanned event occurs then theoretically the existing MRP plan is no longer valid and changes will be required to order schedules, hence the data output from the MRP process must, therefore, be updated.

Unexpected events such as suppliers failing to deliver on time or sudden increases in sales demand are frequently occurring in the manufacturing environment. The MRP process aims at providing materials in the planned quantities at planned times. If unexpected events then occur materials may be late in arriving or stock may run out, hence, preventing processing operations taking place. These stock-outs although temporary can result in under utilisation of manufacturing resources and eventually failure to deliver orders to customers on time.

The major constraint to the frequency with which complete MRP runs can be made is the amount of computer processing time required per run. Normally MRP runs are performed weekly and in order to increase this frequency the amount of data processing required to update the MRP output needs to be considerably reduced. This is particularly true if the MRP system must be capable of reacting to the many and frequent changes that take place in the manufacturing environment. However net change MRP systems in which only those records affected by new or changed information can react much quicker than traditional regenerative MRP systems. To act as a buffer against such unforeseen events the MRP process can allow safety stocks to be held and/or add an allowance on to the normal manufacturing lead times. These procedures are often carried out even though it is generally accepted that efforts should be made to correct the causes of lead time and demand variability. This would allow safety stocks and safety lead time additions to be kept at a minimum. Safety stock levels are determined either using subjective estimates of experienced personnel, or by examining past demand patterns. This method sets the safety stock levels such that a specific percentage of the expected demand over the procurement lead time of the item is covered. The demand dependency of lower level BOM items on their higher level parent items must also be considered when setting levels of safety stocks. If a safety stock level is set for a parent item then the MRP process would automatically generate additional requirements for all dependent items. In general, safety stocks are useful in circumstances where the expected cost of uncertainty justifies their use. However, the use of safety stocks contravenes the philosophy of a JIT environment where stocks of raw material and WIP need to be kept at a minimum (Section 1.3.2).

3.5 Capacity Requirements Planning

Capacity Requirements Planning is the process of determining how much labour and machine resources are required to accomplish the tasks of production, taking into account all component parts and end items in the materials plan. Capacity requirements are calculated by multiplying the number of units scheduled for production at a work centre by the unit resource requirements and then adding in the set-up time. These requirements are then summarised by time period and work centre.

3.5.1 Capacity Requirements Planning in JIT

Long term capacity requirements are employed as an essential criteria to design JIT based production lines and manufacturing cells. Short term CRP is also used to ensure the MPS will not overload the cell. In high variety situations where capacity planning becomes a more complex problem CRP becomes essential in recognising where bottlenecks may occur.

3.5.2 Capacity Planning in non-JIT

Capacity planning in non JIT environments provides planners with details of the capacity requirements needed to process the MRP planned order releases. The outputs from the CRP process are normally 'load profiles' which indicate the amount of work scheduled for each individual work area within the company. Work can be scheduled onto work areas using either finite or infinite loading practices. Finite loading takes into consideration the fact that capacity is limited at each work area and jobs are loaded such that these capacity limitations are not exceeded. Schedules carry detailed information about the order in which jobs should be processed. In practice with finite loading, schedules become out of date frequently due to the many unpredictable events occurring on the shopfloor. Hence, the resources used to keep track of which jobs are on schedule and to prepare finite loaded schedules are often wasted.

Infinite loading ignores the capacity limitations of work centres and will if necessary schedule more than one job at a specific work centre at the same time. The problem of which job to process first is left to shopfloor management to decide.

3.6 Production Scheduling

MRP determines the time buckets in which works orders should be released to manufacturing in order to ensure that MPS requirements are manufactured on time. Jobs released in the same time bucket and which are due for completion in the same period may also require processing at identical work areas. Hence, priority conflicts can result at these work areas and production scheduling is necessary to determine the order in which jobs are to be processed through specific work centres. Production scheduling is the final stage in the manufacturing process and hence planning horizons can be as little as an hour.[78] The main operational aims of production scheduling are to:[80]

a. increase throughput, i.e. attempt to increase the rate of production of items that can immediately be sold and not those that are destined for finished goods inventory,

b. reduce inventories which involves reducing processing batch sizes and production lead times, and
c. reduce operating expenses, such as the direct and indirect labour costs of processing inventory into throughput.

Companies who make to order produce only what the customer requires, hence, the objective is to schedule specific customers orders. This may require introducing orders into existing schedules and ensuring that sufficient capacity is available prior to order acceptance. The criteria used to identify the effectiveness of a schedule would normally be due date[96], i.e. customers would be provided with a due date for delivery of their orders which itself would be established from a knowledge of the manufacturing lead times involved and the availability of production capacity. Detailed scheduling is then performed to ensure that the individual parts and components required to make up the customers order are processed at the correct times and that the order completion date is not exceeded.

Companies who make for stock, produce finished goods that will be held in stock until the customer places an order. The manufacturing company need to decide what products will be made and the order in which products are made. The scheduling process can, therefore, attempt to ensure that production facilities are employed efficiently. In addition, account can be taken of levels of free stock held and the forecast demand for this stock.[97]

3.6.1 Scheduling Methods

3.6.1.1 Forward Scheduling

This method is normally adopted when the objective is to determine the earliest time at which each activity involved in the order processing cycle can begin.[11] The method involves constructing a network diagram to indicate the inter-relationships between the tasks involved. From this diagram the earliest start time for each activity can then be determined and those tasks that form the critical path identified. Using forward scheduling, therefore, the activities on the network diagram are extended from the present date, i.e. all start and finish dates for activities are related to this date.

3.6.1.2 Backwards Scheduling

Backward scheduling may be used when customers orders need to be completed by a specific due date. With this method scheduling starts with the final delivery date and the latest time at which activities need to begin are calculated. Activities must begin by their latest times in order that all subsequent activities will be complete by the final delivery date. As with Forward Scheduling complex products consisting of a large number of assemblies, sub-assemblies and parts each with varying processing lead times can be scheduled using this procedure. When the Backward Scheduling process is complete the initial release date for a works order and the start and end dates for all individual activities can be identified.

3.6.1.3 Optimised Production Technology and Theory of Constraints

The Optimised Production Technology (OPT),[98] manufacturing control philosophy has been specifically developed to provide planning and scheduling facilities for batch manufacturing environments.[99] OPT is an attempt to generate effective schedules using the basic rules shown in Table 7.

These rules are primarily used in generating schedules that enable shop floor resources to contribute towards achieving optimum values of throughput, inventory and operating expenses.[100]

The underlying foundation of OPT is constraint management,[101] or the Theory of Constraints (TOC). The principal objective of constraint management is to establish a process of continuous improvement through synchronised manufacturing. Here synchronised manufacturing can be defined as any systematic method of moving material quickly and smoothly through the production resources of a manufacturing facility in response to market demand,[102] Table 8 summarises the steps in synchronising the manufacturing process.

Table 7 - OPT Rules

RULE 1	The level of utilisation of a non bottleneck resource is not determined by its own potential, but by other constraints within the manufacturing system.
RULE 2	Utilisation and Activation of a resource are not synonymous.
RULE 3	An hour lost at a bottleneck resource is an hour lost for the whole system.
RULE 4	An hour saved at a non bottleneck is just a mirage.
RULE 5	Bottleneck resources govern both throughput and inventory in the system.
RULE 6	The transfer batch size may not, and many times should not, be equal to the process batch size.
RULE 7	The process batch size should be variable, not fixed.
RULE 8	Capacity and priority should be considered simultaneously not sequentially. Schedules should be set by considering all constraints simultaneously.
RULE 9	Balance flow not capacity.
RULE 10	The sum of the local optimum is not equal to the optimum of the whole.

Table 8 - Synchronising Manufacturing Processes

1. Identify the constraint resources.
2. Identify work centres where inventory accumulates.
3. Look for late expedite pattern in parts produced at constraint resources.
4. Identify consistently late orders.
5. Place time buffers in critical locations to protect throughput.
6. Use buffers in front of constraint resources to keep them running.
7. Use buffers at assembly points of convergence to assure timely output.
8. Use buffers at end of the production process to meet specific customer orders.
9. Determine the production schedule for the constraint resource.
10. Link the constraint resource to market demand, looking at the order lead times between the constraint resource and the shipping buffer.
11. Trade off the constraint resources' limited capacity between process and set-up times.
12. Control release of materials to the production floor in order to feed constraint resources.
13. Backward schedule from the constraint resource to gateway operations.
14. Establish priority rules to determine the sequence in which jobs are to be processed when conflicts arise.
15. Move material processed on the constraint resource quickly and smoothly through the remaining operations.
16. Forward schedule work stations that follow the constraint resource.
17. Allow transfer and process batches to vary in order to assure smooth materials flow.

3.6.2 Priority Control

In non-JIT situations when capacity loading conflicts arise between competing jobs, the priority of each job needs to be determined. Normally priorities are based on scheduled start dates, i.e. the job with the earliest scheduled start date is given priority over those jobs with later start dates. Each works order is, therefore, assigned a priority number which is used by operators to identify the next job that they should process.

When conflicts arise at work centres or management wish to improve productivity then the priority of jobs can be determined using other 'dispatching rules'.[103] There are many types of dispatching rule, the majority of which are 'static rules' in that they only consider the scheduling situation at a given work centre at a specific point in time. In addition, these rules do not consider the relationships between the BOM items that make-up a finished item and as such they are irrelevant in a MRP environment.[104]

The dispatching rule most often used in a MRP environment is the 'critical ratio'. This is used in its 'dynamic' form by recalculating the value of a job's critical ratio as it progresses through the production system. In order to do this it is necessary to monitor the progress of each job and to use a computer to constantly update the 'processing time remaining' and the 'time left until the due date'. The advantages of using the critical ratio are that it considers the cumulative lead times involved in processing jobs, all jobs can be progressed according to their due date and jobs that are behind schedule can be identified.

3.6.3 Production Scheduling Problems

The main problems identified at this planning stage are as follows:

1. At this level of planning the frequency with which disruptions to planned events take place are at their greatest, hence production schedules are frequently changed. This happens regularly in HV/LV manufacturing environments, where the unplanned events listed in Table 9 are frequently occurring.

Table 9 - Unplanned Events that Disrupt Production Schedules

a.	machine breakdowns
b.	variability in operator work rates
c.	bad quality
d.	changes in customer orders
e.	unreliable suppliers
f.	employee absenteeism.

2. Normally the final details of a schedule are fixed only immediately prior to its release to production in order that the most recent disruptions to manufacturing can be taken into consideration. Often, therefore, the optimum use of manufacturing resources such as labour equipment and tooling cannot be achieved.

3. In order that the manufacturing resources of an organisation can be used effectively the scheduling function must maintain a system that is capable of developing efficient schedules and must know what criteria are important in determining the efficiency of a schedule. These criteria are varied in nature and importance and change over time leading to difficulties in ensuring that the best criteria are being used to develop schedules.

4. The frequency with which disruptions to production operations occur make it necessary to have a more responsive scheduling mechanism than the MRP process which is normally updated only weekly.

5. A high degree of planning and control is required over each job on the shop floor to ensure its progress through to completion. This tends to increase the indirect labour costs of expediting and production control.

6. Priority control inevitably involves delaying items of a lower priority, which leads to a build-up in WIP.

7. Priority control circumvents the problem of scheduling and does not enable improvements to be focused as within a JIT system.

8. Production scheduling initially uses the MRP planned order releases. However, job priorities may need to be modified to take into account different circumstances such as:

a. instances when delivery lead times given to customers are less than the MRP planning lead times,
b. reducing the priority of orders for stock replenishment to allow actual customers orders to be progressed faster, and
c. varying the manufacturing lead times depending on the delivery promises given to customers.

9. The availability of accurate, reliable and up-to-date data is the key to successful scheduling within a MRP environment. As previously stated this requires detailed and strict working procedures to enable data inputs to be carried out in a timely and accurate manner. This requires frequent data inputs from the shopfloor, which has many associated problems, such as:

a. the frequency with which information can be passed back to the MRP system, the shopfloor information may have to be passed back by operators who may not have sufficient time to perform this task, and
b. inaccuracies in gathering data due to lost, misplaced or unlogged jobs awaiting rework.

10. In non-JIT manufacturing environments there are many factors to be taken into consideration when choosing a scheduling procedure, i.e.:

a. complexity of use of the various methods available,
b. the number of planning variables considered, i.e. in practice most methods concentrate on a limited number of variables, such as cost, due dates and WIP, and

c. the need to make full use of bottleneck resources.

11. No techniques have as yet been developed that can satisfactorily cope with the complexity of most scheduling problems. For example in a company that has 50 batches in progress and a shopfloor with 10 work centres there are literally thousands of feasible sequences in which batches can be processed on any one machine. The scheduling problem is to find the best sequence from amongst so many. The scheduling methods used in practice depend on the volume of materials being processed and hence, on the type of manufacturing system in use i.e., high volume/continuous processing, flow line/assembly line manufacturing or medium volume batch production. Also the type of service offered to customers, i.e. make to order, make for stock, will effect the criteria that are considered relevant and hence the scheduling methods used. In JIT environments scheduling is either limited or unnecessary by the way the system is designed, i.e.:[12]

a. the production line is designed to cope with only a limited amount of component variety,
b. normally it is possible to identify the best acceptable sequence with which to process parts and any divergence from this sequence results in lower efficiencies,
c. total flexibility to change process sequences is not possible,
d. current methods of sequencing are inadequate when too much variety is introduced into the system, and
e. one of the main aims of JIT, however, is to develop a leveled production schedule such that complex scheduling procedures become unnecessary.

Chapter 4

4. JIT Infrastructure

4.1 Introduction

In order for JIT manufacturing to be successful the problems that arise when inventory reductions take place must be resolved quickly and permanently. These problems can normally be resolved by performing one or more of the tasks listed in Table 10. However, it is important that a company possesses an appropriate infrastructure, in terms of organisation, team working, resources, knowledge, expertise and culture, in order that the removal of these problems can be accomplished without large increases in indirect costs.

Table 10 - JIT Procedures for Eliminating Problems

1.	Simplify work methods.
2.	Improve work methods.
3.	Improve operator commitment to quality.
4.	Reduce machine set-up times.
5.	Increase job standardisation.
6.	Improve layout of work areas.
7.	Reduce material handling.
8.	Improve work flow rates.
9.	Improve the processing consistency of machines.
10.	Improve machine reliability.
11.	Reduce machine repair times.
12.	Reduce process batch sizes.
13.	Reduce inter-process re-order levels.
14.	Reduce work-in-progress levels.
15.	Improve product designs.
16.	Reduce the number of assemblies stocked.
17.	Increase parts standardisation.
18.	Improve control over suppliers quality and delivery performance.
19.	Improve control over own quality and delivery performance.

The main areas, therefore, that should be addressed when developing an appropriate infrastructure are:

a. reduction of set-up times,
b. removal of quality problems,
c. improving machine reliability,
d. improving the responsibility, accountability and authority of shopfloor operatives,
e. improving the manufacturability of product designs,
f. improving relationships with suppliers,
g. continuously striving for further improvements, and
h. identifying and using appropriate performance measurements.

Each of these areas will now be examined in detail.

4.2 Set-Up Reduction Infrastructure

Machine set-up time can be defined as the elapsed time between manufacturing the last part from an outgoing lot to the first part from an incoming lot. The set-up time required to change from one part to the next is directly affected by the commonality of the tooling, and the operator's relative experience for setting up. Set-up time is typically comprised of the four tasks listed in Table 11.

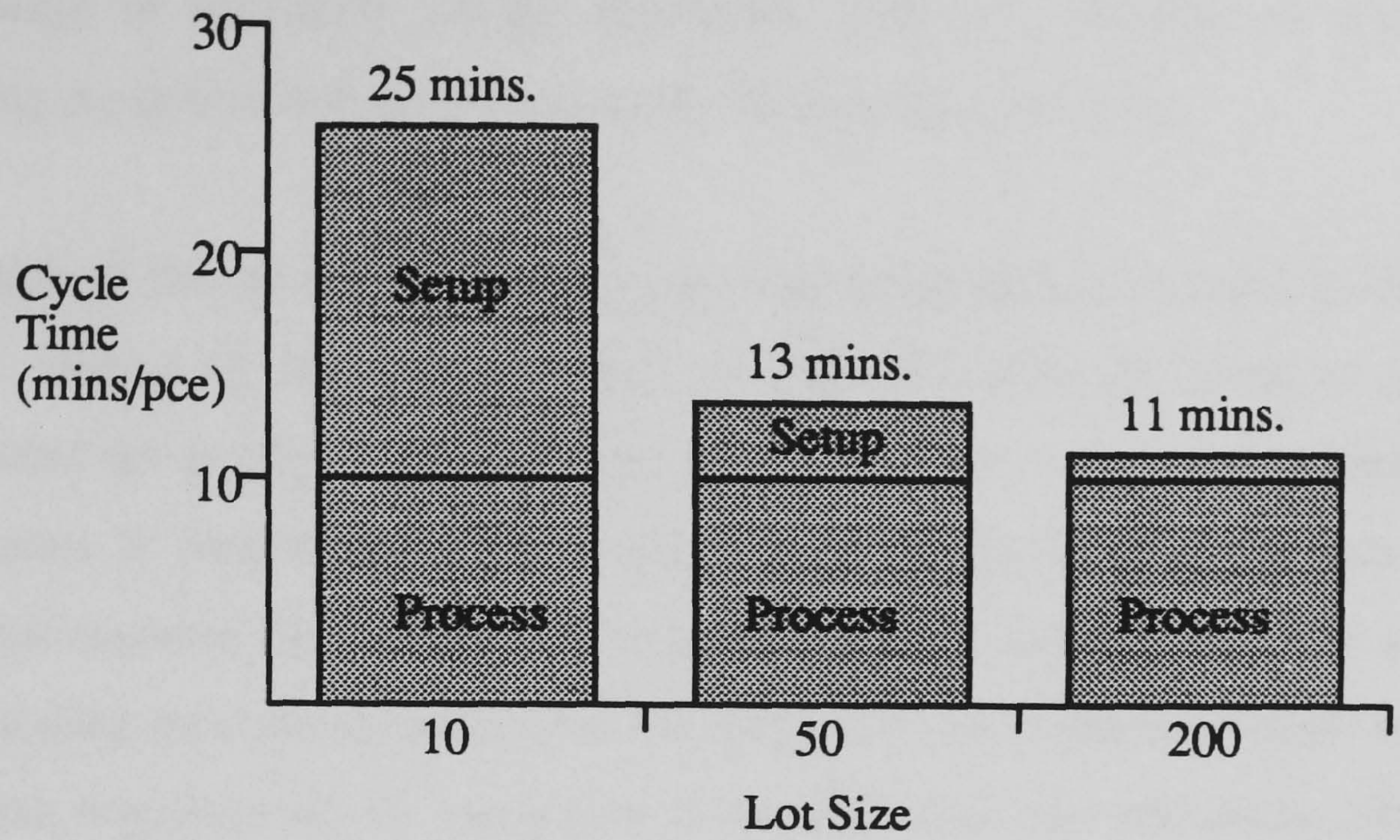
Table 11 - Set-Up Time Reduction Tasks[105]

Task	% Task Time
Preparation of materials, e.g. dies, jigs and fixtures	30%
Clamping and removing dies and tools	5%
Centering and determining dimensions of tooling	15%
Trial processing and adjustment	50%

4.2.1 Set-Up Time Vs Batch Size

The small production lot sizes of the JIT system require reduced set-up times to allow for the numerous change-over operations needed,[106] i.e. small batches involve more frequent machine set-ups. As lot size is, therefore, reduced, lot throughput time decreases, and set-up time consumes a larger fraction of cycle time at each operation as illustrated in Figure 5. Consequently higher costs can result unless steps are taken to reduce set-up times. Therefore, it is necessary to reduce set-up times to enable frequent changeovers and maintain effective capacity.

Figure 5 - Batch Size Vs Cycle Time



The use of smaller batch sizes that result from reductions in set-up costs are essential to the efficient operation of the JIT philosophy, since they allow:[107,108,109]

a. inventory costs to be reduced,
b. the manufacturing system to possess greater flexibility for changing over from one product to another, hence a greater variety of parts and products can then be economically produced,
c. a smooth flow of materials through the manufacturing system, without disruptions in material flow when a variety of products need to be manufactured, and
d. an operator to be made aware much sooner of any defective items that have been passed from an upstream work area, hence the overall quality of the parts processed can be improved.

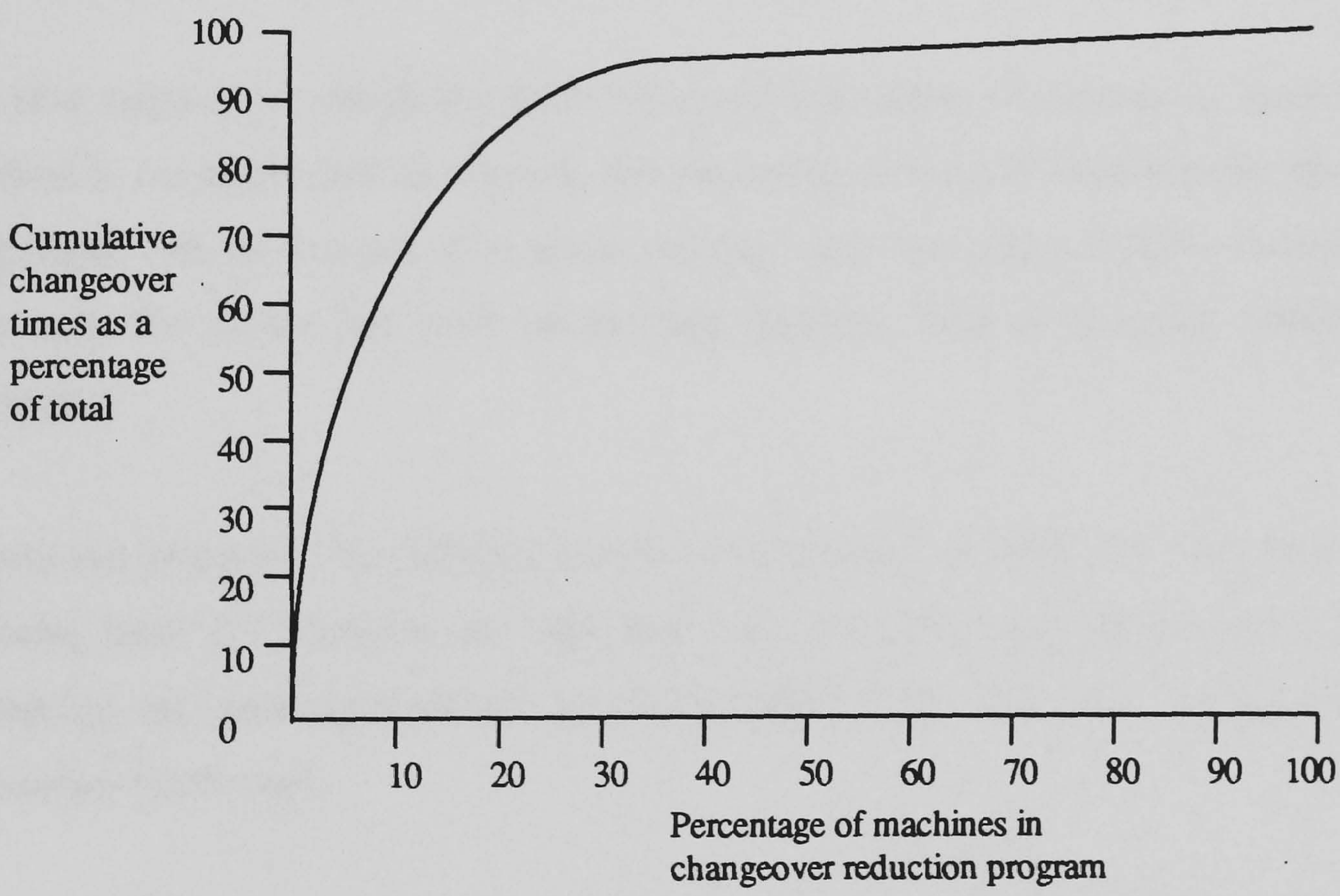
In order to implement JIT control practices it is, therefore, necessary to exert great efforts to reduce equipment set-up times.

4.2.2 Set-Up Time Reduction

It is important to tackle only those set-ups that have been identified as problems through the forced removal of inventory, hence resources are not wasted on set-ups which do not as yet disrupt material flow.[110] JIT procedures also involve seeking active ways of abolishing set-ups altogether. This can normally be achieved by increasing the design and processing standardisation between parts.

An analysis of the set-up times of the case study organisations involved in the current research (Figure 6) identified that only a small proportion of machines and parts experienced the problems of long set-up times. However, the problem within HV/LV environment is determining if the equipment with long set-up times constitutes a bottleneck resource. If this is not the case then there are limited benefits to be gained from reducing such set-up times. In a JIT environment it is normally easier to identify bottleneck resources by the reductions in material flow rate that occur, hence, it is easier to identify the set-up times that must be reduced.

Figure 6 - Pareto Analysis of Set-up Times



Eliminating the problems of high set-up times has been approached in two basic ways, i.e. by reducing the set-up times, (process based methods) and by removing the need for set-ups (frequency based methods).

4.2.3 Process Based Methods

Process based methods seek to complete set-up tasks while the machine is running and to simplify each step in the changeover process. Although there are a number of process based methods[108,109,110] each is a modified version of the method developed by Shingo,[111] i.e. the Single Minute Exchange of Dies (SMED) technique.

The basis of the SMED system is the recognition that all tasks involved in the set-up process can be classified has being of an internal or external nature, i.e. an internal element is a task that must be performed while the machine is stopped whilst an external task is one that can be completed while the machine is still processing. Set-up elements are also classified by where they are performed, i.e. on-site or off-site elements. On-site elements are those tasks that are completed in the work area whereas off-site elements take place outside the work area and therefore may be performed by other individuals or service departments.

The time required to complete a given set-up depends upon the average or mean time required to complete each set-up task, the frequency with which each element must be performed, and the amount of random variation from the average time required for each task. To reduce the total set-up time, each of these components should be minimised.

A practical procedure for reducing set-up times is shown in Table 12. This table also indicates how JIT elements are designed such that they assist in the process of identifying and reducing those set-ups that prevent further reductions taking place in processing batch sizes.

Shingo[111] claims that after separating internal and external tasks and performing external tasks whilst the preceding batch is still being processed a 30 to 50% reduction in set-up time can be obtained. In addition, if internal elements can be converted to external elements, for example by making additional tooling available, then set-up times can be reduced by a further 25%.

Table 12 - How Set-up tasks are aided by JIT Tasks

Set-up procedure	JIT task that assists
Prepare a detailed study of existing set-up operations.	Inventory reduction highlights bottleneck machines on which to concentrate set-up reduction exercises.
Determine if any set-up tasks can be eliminated.	Group technology, design modifications and design for manufacture.
Determine if improved methods can be found for performing set-up tasks.	Cell layout, team work promoted by cellular manufacture.
Ensure that all tools and equipment are readily available in locations that are easy to reach well before they are required.	Cell layout design provides suitable areas for storing tools.
Perform as many of the set-up tasks as possible whilst the current batch is being processed.	Multi-skilled workforce and teamwork.
Ensure that the machine is only stopped when necessary.	Team work.
Use jigs and fixtures designed to achieve fast changeover times.[112]	Design integration with manufacturing.
Ensure that optimum set-up procedures are identified, standardised and practiced regularly.	TQM approach and team work will be of benefit.

In addition, methods have also been developed by which the time required to perform both internal and external tasks can also be reduced leading to a further 15% reduction in set-up times. Shingo presents four methods to streamline set-up elements, i.e.:[106]

a. reduce machine adjustments, e.g. by placing predetermined stops or calibrations on frequently adjusted areas,
b. use of quick release clamps, here investment in jigs, fixtures and equipment modifications have produced pronounced set-up reductions.
c. complete tasks simultaneously by the use of additional set-up operators, and
d. introduce mechanisation, for example, a hoist may be used to help an operator lift heavy tooling into a machine. Shingo recommends that mechanisation should be the last method to reduce set-up time since if implemented too soon, an inefficient set-up procedure may become mechanised.

Decisions relating to set-up reduction have been described as difficult and complex, involving multiple criteria, such as automation levels, facility layout, throughput required, the variety of manufactured products and worker characteristics. Hence, knowledge based systems are currently being developed that support management decision making.[113]

The set-up reduction process requires a high level of commitment from the personnel who form the set-up team. Benefits can be gained, even with relatively little investment, i.e. in terms of improved quality, reduction of lead time and reduction of work-in-progress.

4.2.4 Frequency Based Methods

Frequency based methods seek to remove the need to perform set-up operations by:

a. using improved scheduling techniques,
b. using design changes,
c. investing in smaller purpose built machines,
d. buying components rather than by making them in-house, and
e. grouping parts according to type of set-up, and then scheduling, families of components that are similar in terms of their set-up requirements. Hence, both the

amount of tooling that needs to be changed or adjusted and the frequency of performing a complete or major set-up is reduced.

4.3 Quality Infrastucture

In current terms poor quality is defined as variations from any type of standard, and includes for example variation in machine speed, tooling dimensions, set-ups and damage to materials.

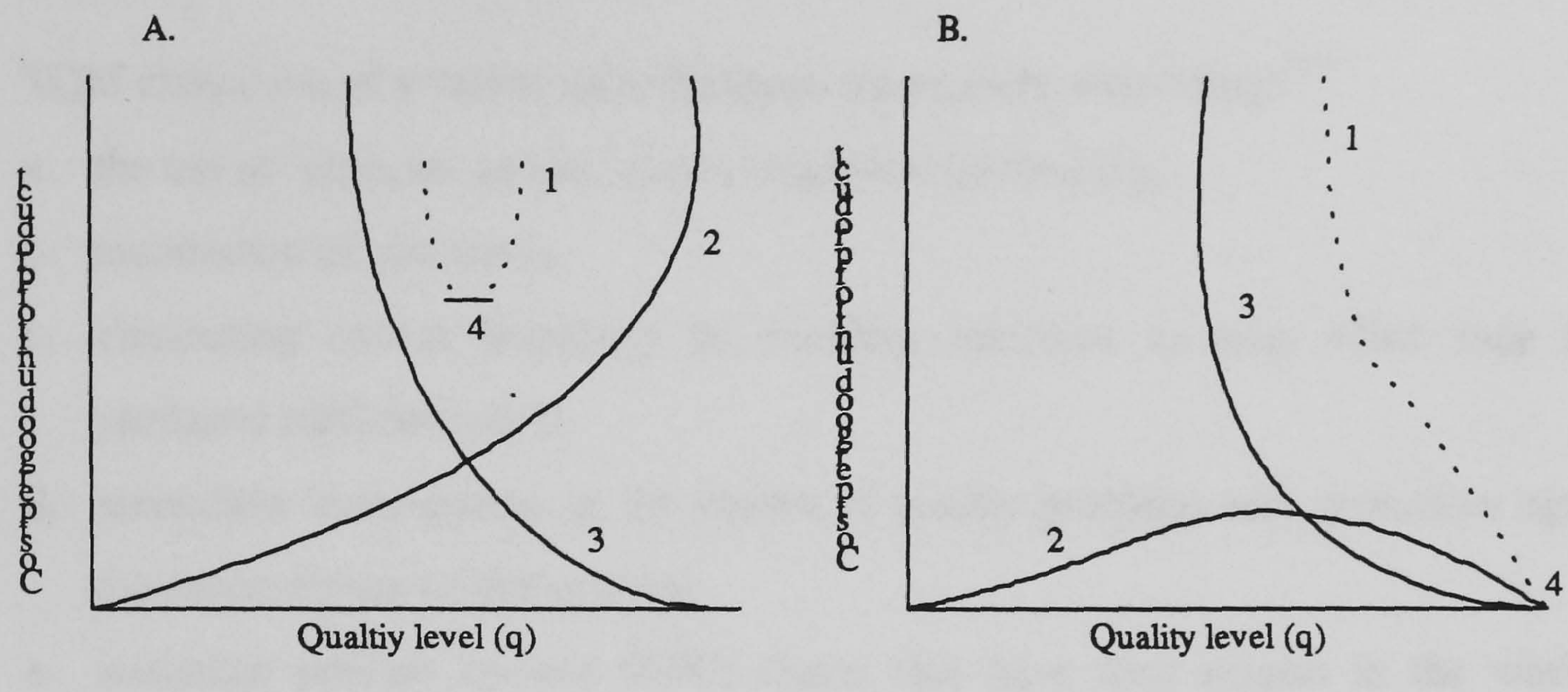
The management and control of product quality is an essential element to the success of JIT operations since when inventory is reduced or eliminated, particularly safety stocks, the production of defective items has a more direct effect on the ability of an organisation to supply customers with their orders.[114]

The cost of quality can be broken into the following categories:[115]

a. appraisal costs, e.g. the costs of inspection,
b. internal failure costs which include the costs associated with repair, scrap and damage,
c. external failure, i.e. those costs, such as warranty costs, that arise through sending poor quality goods to customers, and
d. prevention costs which include the costs of monitoring and education.

It is generally believed, that as appraisal and prevention activities, and therefore costs, increase the costs of failure will decrease as illustrated in Figure 7A. However, from this figure, the total costs of quality can be seen to be at a minimum at a specific level of quality. This tends to suggest that improving quality above this level will lead to an increase in the overall costs of quality and is, therefore, uneconomic. An alternative view, Figure 7B, however suggests that prevention and appraisal costs would begin to decrease after a specific level of quality has been reached. The reason given for this is that the organisation would begin to make prevention a part of the operators' job and avoid the increases in indirect labour costs associated with increasing quality activities using indirect quality control personnel.

Figure 7 - Quality Cost Models



1 total quality costs
2 costs for prevention and appraisal
3 internal / external failure costs
4 minimum total cost point

4.3.1 Total Quality Management

The traditional approach to quality management and control within a JIT environment is TQM which adopts a continuous improvement approach to increasing customer satisfaction.[116] Total Quality Management, according to Munro-Faure,[115] is a proven, systematic approach to the planning and management of activities which can be successfully applied to both JIT and non-JIT environments. Of the HV/LV organisations investigated during the current research all were utilising or implementing the principles of TQM, indicating the impact of this method of improving quality.

TQM cannot be implemented within individual sections of an organisation, i.e. Sandras[117] states that quality "must be present in the whole chain from the supplier to the customer". Hence TQM must be a total approach, permeating every link in the organisation chain, including suppliers. Hence, TQM involves developing, establishing, maintaining and controlling various groups within an organisation to ensure the attainment of full customer satisfaction and company profits. In this respect, successful implementation of TQM is dependent on the workforce and how well they assume responsibility for maintaining the quality of their work.[118] The elimination of all possible causes for poor quality should be aimed for, i.e. as stated in Section 1.3.2, the ultimate goal should be producing zero defects.

TQM makes use of a variety of techniques, the primary ones being:[119]

a. the use of 'plan, do, action' cycles originated by Deming,
b. automation of processes,
c. eliminating excess inventory by enabling machines to stop when they have produced sufficient parts,
d. immediate investigation of the causes of quality problems and protection against the reoccurrence of defects, and
e. statistical process control (SPC) charts that have their origins in the work of Walter Shewart.[120]

With respect to SPC, modifications to traditional approaches have been implemented within JIT environments, i.e.:

a. emphasis on chart design to provide statistical notice about changes in the control of processes that are likely to result in quality problems,
b. measurement in the areas where the defects occur,
c. operator responsibility for the quality of the products or components being manufactured, and
d. the use of 'run' diagrams that through their use individual measures rather than averages of sample batches provide more precise measurements of quality. Although the run diagram is suitable for small lot sizes, i.e. between 50-100 items, in HV/LV situations these quantities may represent an unusually large batch size. In addition, the inspection and plotting of every unit is costly. SPC techniques that use normalised measurement data have therefore been developed to cope with such low volume production.[121]

4.3.2 Operator Involvement

Of major importance to the successful implementation of TQM is operator responsibility, i.e. in order for TQM to successfully operate the knowledge and the experience of the workforce is required. To benefit from this knowledge and experience, one approach has been to organise groups to attack problems, i.e. through the use of Quality Circles (QC) or small group improvement activities (SGIA).[122] Quality Circles use a facilitator to provide training in quality concepts, objectives and techniques, such as process flow charts, Pareto analysis, fishbone diagrams and run diagrams, for process analysis and improvement to the remaining QC members.[123] Hence QC's are able to consider a wide range of problems and communicate their achievements and experiences to other QC's within the organisation.

QC's are permanent groups, whereas SGIA's are ad hoc groups, i.e. an SGIA is formed using both operations and technical support personnel who are assigned to a specific project, provide regular progress reports to management or a steering committee, and usually disband when the project is completed. The basic principle of SGIA's is to ensure that the personnel who the quality problem affects are able to contribute their expertise to its solution.

Within a JIT environment, the primary responsibility for ensuring that all items are made to an acceptable quality is given to the shop floor operators and supervisors. Ensuring that operators do accept responsibility for the maintenance of quality involves attempting to change their attitudes to the work situation. In this respect, shopfloor operators must be both trained and encouraged to seek to achieve excellence at all stages of manufacturing and assembly. In general, this is not seen as a particular difficulty with respect to HV/LV manufacturing environments, due to their predominant use of highly skilled shopfloor personnel.

In summary, commitment to the prevention of defective items is essential and promoted by the activities listed in Table 13:

Table 13 - Promoting Commitment to Quality

1.	Establishing systems of process control at each work station.
2.	Ensuring that the quality of an item can be and is easily measured and that employees are trained to measure quality, collect quality data and to identify causes of defects by analysing the data collected.
3.	Ensuring that quality problems are visible to both shop floor operators and managers by using simple control charts to monitor quality levels.
4.	Using charts to record the company's progress towards its primary aim of producing zero defective items.
5.	Insisting that all quality standards and specifications are achieved.
6.	Ensuring that quality is measured as the parts are processed.
7.	Empowering workers with the authority to stop both the process and the production line if the process goes out of control and quality standards are not being achieved.
8.	Making employees responsible for correcting their own quality defects, if necessary, after their normal working hours.
9.	Insisting on 100% inspection at each work station both for part processed items and finished goods.
10.	Automating the inspection process whenever possible.
11.	Ensuring that products are designed to avoid difficulties during manufacture and to minimise the possibility of defective items being produced.
12.	Developing effective working methods that make it difficult for a defective part to be produced.
13.	Ensuring that the processing equipment used makes it easy to produce good parts and that quality specifications are within the 'process capability' of equipment.
14.	Encouraging good housekeeping so that operators work in clean, well maintained environments, to promote better working practices.
15.	Employing preventive maintenance techniques to enable the processing reliability of machines to be checked regularly.

16. Scheduling production lines at less than their full capacity in order to avoid errors caused by haste.
17. Providing instant feedback to those operators who are responsible for producing defective items.

4.4 Maintenance Infrastructure

According to Jahnig and Ettkin,[124] in order to support Just-in-Time manufacturing, equipment breakdowns must be eliminated and production machines must be in almost perfect condition. As with quality problems, this is again due to the removal of safety stock and the implementation of process orientated cells, i.e. in a cell with little in-process inventory, if one machine stops then the whole cell quickly ceases to function as each machine runs out of WIP.[125]

The need for high levels of machine 'up-time' has lead to the development of Total Productive Maintenance, (TPM), methods and brought about developments in the scientific maintenance of production machinery,[126] i.e. reliability. The distinctive features of TPM when compared with traditional maintenance approaches are as follows:

a. TPM aims to maximise overall equipment effectiveness,
b. TPM establishes a thorough system of preventive maintenance (PM) for the equipment's entire life span,
c. TPM is implemented by coordinating the activities of various departments including engineering, operation planning and control and maintenance,
d. TPM involves every single employee, from top management to workers on the floor, and
e. TPM is based on the promotion of PM through autonomous small group activities.

Emphasis is placed on the collection of breakdown and repair data in order to calculate for individual machines the mean time between failures (MTBF) and the mean time to repair (MTTR). This information can then be used to target the most likely causes of failure in order to increase the MTBF and reduce the MTTR. This is accomplished mainly by tightening quality control procedures on components, improving set-up procedures, building in greater safety factors in design and also improving the training and effectiveness of the maintenance department.

Most industrial equipment falls into the class of complex, maintained equipment in which components are replaced when they fail. In this respect there are several distinct types of failures, i.e.:

1. Early life failures, i.e. failures that occur when the equipment is placed in service and are caused by sub-standard components, improper installation and non-familiarisation of shopfloor personnel with the equipment.
2. Wearout failures, occur at random times during the operation of equipment, due to components reaching the end of their operational life.
3. Random failures, which are the result of variations in the loads imposed on any given component and the strengths of supposedly identical components. Random failures are essentially constant over the lifespan of the equipment and are normally small, being overshadowed in most other cases by other failures.
4. Design deficiency failures are the result of a design errors, they show up as a series of wearout failures relatively early in the life of the equipment. It will be inevitable, however, on new designs that have not been thoroughly tested, and on special 'one-off' machines used in industry. The worst design problems are usually corrected early until the failure rate is reduced to an acceptable level. At that point, design failures become indistinguishable from minor wearout failures.

Shopfloor personnel should also be involved in ensuring that the frequency with which machines breakdown is reduced. Their tasks should be to perform routine servicing of equipment. They are also of use in helping to detect when machine operation varies from the normal. Hence they may help to correct problems before more serious trouble develops.

4.4.1 Condition Monitoring

Condition monitoring is based on the observation of a part while it is running to ascertain the level of wear within that part and to ensure that the part can be replaced before it fails rather than after failure occurs.

There are numerous ways of monitoring the wear of components, the primary and simplest of these is the visual method, using the eyes, intrascopes, and miniature TV, operators of equipment are often the best guide to their operable state. Other methods include monitoring pressure of the oil within the system and temperature readings of bearings and water cooling system. Using the size of wear particles can give an accurate estimate of exactly when a part will fail.[127] Vibration and noise are also indicators of wear within a system although the relationships are more complex.

4.5 Personnel Infrastructure

According to Heard[128] the implementation of JIT techniques requires a change in the attitude of management to their shop floor staff and the attitude of shop floor staff to their work. This change in attitude and responsibility is essential if shopfloor operators are to contribute effectively in set-up, quality improvement and maintenance tasks as described in Sections 4.2 to 4.4.

In addition, a change in attitude of shopfloor operators is essential if manufacturing of small batches is to be accomplished economically. That is, when a defective item is produced the sooner it is discovered by a downstream operator the sooner action can be taken to prevent further poor quality being made. The use of smaller batch sizes can achieve this fast feedback between operators since work is passed down the line at more frequent intervals. However, in order to achieve feedback of quality data operators must be motivated and trained to identify quality problems. Fast feedback of quality data engenders:

a. reported then shop floor personnel must be motivated towards finding long-term solutions.

In order change the attitude of operators to work tasks the support and involvement of management, at all levels, is essential.[129] In this respect management's responsibility is to encourage a change in working culture, i.e.:[130]

a. provide an environment where everyone manages their own area of responsibility, i.e. this requires self management skills, the ability to follow standard procedures, problem solving skills, analytical skills, teamwork, vertical and horizontal communications, technical skills, management and presentation skills,
b. develop a blame free environment and guide and support the cycle of improvement,
c. ensure that supervisors become trainers, motivators and leaders of improvement activities,
d. provide effective communications, e.g. use visual aids and share information, hold regular improvement meetings,
e. emphasise improvement by implementing effective reward systems, i.e. monetary and non-monetary, individual and group,
f. ensure that all personnel look on the next process as a customer,
g. ensure that improvements are initiated and led by senior management,
h. focus on improving shopfloor problems, e.g. quality, costs, delivery and safety,
i. promote - ownership of problems, group dynamics, barrier elimination, setting clear objectives, process orientated improvements, the identification of individual customers, the reduction of fear, respect for others opinions, visible management, the exposing of weakness, bottom-up communications and encouragement of everyone to be honest,
j. develop manufacturing strategies and operating plans with the help of subordinates,
k. develop a management style that encourages cooperation, trust and openness,
l. develop a reward system that promotes cooperation,
m. institute continuous training programs, and
n. support and recognise both group and individual efforts.

Generally in order to obtain operator commitment management must seek to:

a. take an interest in shop floor workers,
b. listen and act on advice and suggestions from shop floor personnel,
c. initiate discussions and activities between the personnel in a group,
d. implement training programs designed to train personnel in quality control, machine servicing, routine maintenance, group working, operating additional items of equipment and performing additional manufacturing tasks,
e. develop in workers the correct attitude to their work, commitment, motivation. and a feeling of responsibility, and
f. organise work to ensure that conditions are suitable for shop floor personnel to work in groups, A flexible, multi-skilled workforce is basic to the efficient operation of a kanban control scheme. A flexible labour force enables JIT systems to cope with fluctuations in the demand for products. When demand rises then the number of machines an individual operator controls is reduced and temporary workers are employed to 'fill the gaps'.

4.6 Design Infrastructure

JIT calls for close cooperation between product designers and manufacturing personnel. The objective in coordinating the activities of these personnel is to reduce the variety of processes that JIT cells need to perform.[131] In addition, the product design function can also aid in the implementation of other JIT tasks, such as:

a. reducing the number of set-ups required by using common components within different products,
b. reducing the number and length of set-ups by designing parts to use common tooling,
c. improving quality by reducing processing and design complexity, and
d. improving quality by reducing the number of unique part types.

Reducing design variability in this manner leads to better machine utilisation and hence the need for less equipment and floor space. These techniques also enable the production system to respond effectively to market demands by considering manufacturing problems at an early stage in the design process.

The primary design techniques used to ensure that the design function supports the operation of a JIT environment, are variety reduction, modular design, design for simplification and design for ease of manufacture. The overall aims of these techniques are to enable product ranges to be designed with sufficient variety to meet customers expectations, yet still maintain processing complexity and variety within acceptable limits. When designing products therefore the following basic rules apply, i.e.:

a. avoid the unique,
b. standardise design features, e.g. radii, drill diameters,
c. duplicate designs where possible,
d. simplify where possible,
e. minimise processing variability, and
f. minimise product variability.

This technique seeks to design product ranges that contain common parts and sub-assemblies. The use of standard items in this way results in a requirement for fewer different items in larger volumes. During the design stage attempts must be made to ensure that where differences exist between products they are maintained as high in the BOM structure as possible. This leads to variety in the manufacturing processes being maintained at the end of the production sequence. Any changes in market demand or customer order requirements will then have the minimum effect on the work currently on the production line

The designers responsibility in this respect is to design products that:

a. use 'off-the-shelf' components that can be purchased from existing stocks,
b. require common tooling or the minimum amount of tooling,
c. standardise on design features such as bore diameters and corner radii, in order to reduce the number of different tools required,

d. use the lowest possible dimensional tolerances and surface finish specifications commensurate with customers expectations,
e. enable quick set-ups to be utilised, and
f. enable automatic part feeding, orientation and assembly to be simplified.

4.7 Procurement Infrastructure

When implementing JIT, materials and parts should only be delivered in response to a 'pull' command from the shop floor.[132] That is, supplier deliveries must be handled as if they were materials moving between work centres.[133] Under these conditions materials would be delivered in smaller quantities, but there would be more frequent deliveries made. JIT implementation also calls for a significant change in management's attitudes to the purchasing function.[134]

Traditional purchasing techniques involve buying from a number of suppliers and inspecting all deliveries on arrival, in order to:

a. take advantage of the lowest prices offered by suppliers,
b. ensure continuity of supply,
c. ensure parts can always be delivered on time,
d. ensure that production does not suffer if poor quality materials are delivered, and
e. purchase in larger quantities to take advantage of price discounts.

The JIT purchasing philosophy adopts a different approach[135] in that the emphasis is on purchasing from a small number of suppliers with the choice of suppliers being based on their ability to meet stringent quality specifications and provide frequent deliveries of small quantities of materials. Contracts would then be developed with suppliers that whilst specifying the total purchase quantity required over the long-term would allow for short-term changes to take place in the quantities delivered.[136] Dion et al[137] identified the operational changes that need to take place in both the customers and suppliers role if the implementation of JIT purchasing is to be successfully achieved, i.e. Table 14.

Table 14 - Changes Involved with Supplier Partnerships[137]

Operational Change	Change in Buyer's Role
Higher product quality	Some of buyers inspection responsibilities adopted by the supplier
Lower product inventories	The buyer concentrates on flows versus stocks of input material
Reduction in individual order lead time	Less expediting of backshipments
Overall reduction in order lead times	More flexibility and planning
More frequent, smaller deliveries	Transactions become more routine

In addition the relationship with suppliers in a JIT environment would involve:[138,139,140]

a. building strong, enduring relationships with both organisations sharing information and working towards shared goals,
b. buyers being allowed to closely inspect suppliers quality control procedures, inspection records and other records that have a bearing on the suppliers ability to meet JIT conditions,
c. encouraging suppliers to adopt JIT manufacturing techniques themselves by constantly seeking to improve their product quality, reducing lot sizes and increased delivery frequency,
d. working together to maintain the smooth flow of materials through both supplier and customer plants, and
e. motivating suppliers to contribute to the success of the JIT program.

There are benefits that suppliers gain by entering into a JIT supply agreement, these include:[141,142]

a. the supplier is assured of getting increased business from the customer and is not continually involved in re-bidding procedures,
b. the long-term supply contracts agreed with their customers allows the supplier to plan future operations more accurately and effectively,
c. many JIT customers who are large organisations provide their suppliers with assistance in quality control training and the implementation of JIT practices, and
d. suppliers are informed immediately of any modifications to their customers MPS, hence they are more able to integrate their production schedule with that of their customers.

The benefits to be gained by customers of JIT purchasing agreements are:[143,144,145,146]

a. reduced raw material inventories,
b. less rework required as a result of using defective raw materials,
c. reduced inspection,
d. shortened manufacturing lead times as a result of shortened purchasing lead times,
e. increased ability to adapt to changes in customer demand,
f. reduced areas required for goods receiving, in-process inventory, and shipping areas, i.e. ideally materials flow directly to work stations without waiting in holding areas, and
g. the burden of counting parts is often placed on the supplier who should then deliver in standard container sizes, hence making counting by their customers relatively easier.

There are many obstacles to the successful implementation of JIT purchase and delivery agreements. For example the size of the customers firm, if much smaller than the suppliers firm, may render it difficult to impose JIT delivery frequencies on the supplier.[147] A further problem involves the physical distance between the supplier and buyer, that can influence the economic size of batch that can be delivered. However, in this respect, cooperation between suppliers in which they share transportation can reduce the frequency with which any one supplier needs to make a delivery. In addition, several different suppliers in a particular area could ship their orders to a common warehouse and then combine orders for final delivery to customers. Organisations have also relocated their factory premises to be nearer major customers. Building a supplier partnership is an ongoing exercise and if the requirements of the organisation are to be consistently achieved, then the customer/supplier relationship must be open, enabling each side to clearly identify requirements.[148]

4.8 Continuous Improvement Infrastructure

Continuous improvement, i.e. Kaizen, is a process of continually making improvements to the process of converting inputs to outputs. When operating Kaizen, improvement efforts should never cease and improvements should be sought in all areas of manufacturing including equipment, methods, materials, people and information.

Key elements in the continuous improvement process are:[149]

1. Underpinning of continuous improvement with a total quality program that trains the entire workforce in the philosophy and tools of total quality control. This is seen as crucial to creating an environment in which all personnel within the company expect improvement changes to take place.
2. All personnel within the company must work as part of committed teams, use their skills to improve processes, use their initiative to identify problems and seek solutions, never settle for the status quo, continually strive to improve their work, and be willing to contribute the maximum to the benefit of the business. Effective cross-functional teams must be set-up that involve all relevant functions, address root causes of problems, question all company norms and practices and formalise mechanisms to maintain solutions.
3. An environment that contains total flexibility in working practices and flexibility between jobs, single status for all employees, empowered people who feel able to take part in the improvements that take place and a strategic vision that is communicated to the workforce. An environment where the need for continual change is understood and where individuals understand that improvements provide benefits and security for themselves.

4. Standardization - Documentation of new improved methods which should then act as a reference for training and further improvements.
5. Standard methods and tools used for identifying problems, describing current and improved practices, generating ideas for improvement, achieving consensus amongst team members and evaluating and monitoring the results of improvements.
6. Continuous Plan-Do-Check-Action and Plan-Do-Check-Standardize cycles.

4.8.1 Continuous Improvement Cycle

The continuous improvement cycle essentially involves the following basic steps:

1. Identify Problems

Here it is essential that the true causes of a problem are identified and not merely the symptoms exhibited by the problem. Kaizen requires that:

a. problems are always identified at their source,
b. a culture is established that welcomes problems, does not attempt to hide or cover up problems, encourages people to admit problems and work towards achieving solutions to them,
c. focus is brought to bear on identifying problems in the overall process, and
d. priorities are established for solving problems.

Methods of identifying problems include:[122]

a. allocating, to foremen and managers, a period during the day in which to identify problems and work on Kaizen programs,
b. asking foremen and managers to construct long lists of problems,
c. challenging accepted practices,
d. benchmarking, i.e. identifying the key processes which apply to the business, identifying who is the best at performing these practices, finding out how they achieve the best practice and developing programs to implement their procedures,

e. enabling individuals to use cards to document problem areas and improvement ideas,
f. exposing problems by reducing inventory or manpower levels in a production area,
g. standardising method and tooling in order that abnormalities from standards can then easily be seen,
h. using problem checklists, control charts and interviews with personnel, and
i. identifying reductions in cleanliness, organisation, arrangement, neatness, and orderliness.

2. Gather Information and Define Problem

Once the true cause of the problem has been found it is necessary to gather information in order to accurately and precisely define the problem. The factors that have a significant effect on the problem must be included in this definition. Too narrow a definition of a problem may exclude important factors that effect the problem whereas too broad a definition may include variables that are irrelevant.

Appropriate tools and techniques must be used to gather information, e.g. checksheets, control charts, flow process charting and time study. These techniques have also been shown to be aid to identifying solutions to problems.

3. Generate Alternative Solutions

When attempting to solve a problem it is always important to generate a number of alternative, feasible solutions. This increases the chance of identifying the optimum solution but adds to the effort required to determine which solution is best. There is, therefore, always a limit on the number of solutions that can be identified and compared. Alternative solutions can be generated by:

a. using tools such as cause and effect diagrams to suggest solutions,
b. using a suggestion scheme to generate ideas for improvements, and
c. asking relevant questions concerning the job or work that causes the problem.

4. Identify the Best Solution

In order to select the best solution it is necessary to consider the objectives in removing the problem and the criteria that will be used to evaluate the alternatives. Hence, it is necessary to decide what needs to be improved, how to measure the improvements and to set goals and targets for improvement efforts. Once these have been established each alternative solution must be evaluated against the resulting criteria.

5. Implement Best Solution

When implementing the chosen alternative it is important that:

a. methods are developed to ensure that operators adhere to the new solution,
b. performance measurements are implemented that ensure operators do not deviate from the procedures,
c. use agreed procedures,
d. ensure proper training of all workers concerned, and
e. ensure management make it easy to use new procedures for example by making it easy to find the required resources.

6. Monitor Solution

Once the new method is installed and in use it is necessary to use regular audits to identify the results of improvement efforts and to display these results so that all can see them. In order to perform an audit it is necessary to collect and record data that can be used to check if plans have been executed as required and if objectives have been achieved by comparison with planned targets. In this respect if aims have not been achieved then it is necessary to analyse the results of the audit in order to identify the root cause of non-achievement and hence develop countermeasures.

7. Standardise

If plans have been satisfactorily implemented then it is essential that the new procedures are standardised. This involves documenting the procedures in order to preserve know-how, assure quality, establish costs incurred, ensure delivery and safety and act as the basis for audit and diagnosis hence making maintenance and improvement possible.

Methods must be developed for ensuring adherence to all standard procedures, i.e. by training to new standards, making correct procedures become a habit, using standard equipment and making standards objective, simple and conspicuous.

4.9 Performance Measurement Infrastructure

Effective measurement of performance is essential to the management process of setting and achieving goals. Methods of measuring performance are, therefore, essential and should according to Roman[150] provide valid, timely and accurate information regarding how good or bad a certain function or activity is being performed compared to a stated goal or objective. In order to measure the relative success of a manufacturing organisation in achieving its objectives, the traditional method has been to use 'cost' based performance measurements. However such methods have recognised weaknesses when attempting to measure the relative success or failure of time based strategies such as JIT and quick response.[151,152,153] Novitsky[154] also highlighted additional limitations when using cost based measurements in that they could result in the improvement of individual functions without necessarily optimising the performance of the whole organisation. In addition, both their intended aim could be bypassed such that they no longer reflected what is happening in the organisation and their use may not always reflect the situation on the shopfloor.[155] However, although such limitations have been identified with the use of traditional cost based performance measurements, Novitsky has stressed the importance of using a balanced mixture of both traditional cost based measures and new time based measures.

Performance measurements are intended to inform their users of how well activities are being carried out with respect to a target figure. Hence, there is a need to provide such information at various management levels. The number of levels would depend on the organisation but at a minimum would need to include senior management, departmental management and individual or teams of shopfloor operators. At the senior management level, performance measurements need to focus on lead times, delivery reliability, quality, costs, inventory, product variety, and new product development.[156] At this management level the indicators used should monitor the performance of the organisation as a whole and inform management if improvements have been achieved. The information provided by such measurements at this level should, therefore, enable senior management to make strategic decisions and avoid the problem identified by Woodcock,[157] i.e. of providing senior management with the type of information that merely enables them to assess how well their subordinates have been performing. At departmental management and shopfloor operator levels there is a wide range of performance measurements available examples of which are listed in Table 15.[158,159,160,161,162]

Table 15 - Performance Measurements

1. Lead time related.
Supplier lead times.
Internal process lead times.
Manufacturing lead times.
2. Performance to schedule related.
Supplier delivery to promise.
Master production schedule performance.
On-time shop order completion.
3. Delivery performance related.
Number of on-time deliveries.
Number of past due orders.
Availability.
4. Quality Related
Number of Defective Parts
Percentage Return on Sales.
5. Factory Related
Space Requirements
Number of Staff to Direct Workers
6. Inventory related.
Work-in-progress levels.
Number of inventory turns.

When deciding which performance measures to adopt Woodcock[157] suggests using the order winning criteria / order qualifying criteria approach to initially compare the performance of a manufacturing system against. In this way higher level performance measures could be identified. Wantuck[155] then suggests deriving lower level performance measures from the higher level ones adopted. This 'top down' approach is essential to ensure that such performance measurements actually track activities that are important to the achievement of the organisations overall goals. Performance measurements must, therefore, act as a tool to enable management to understand and measure the relationships between higher level policies and operational procedures[163]. In this respect, to assist management in enforcing measures that can improve inefficient situations, it must be possible to aggregate lower level performance measurements into single higher level ones.[164] For the basic performance measurements used to derive the higher level ones, particularly those that are derived at the shopfloor level, it is also necessary to ensure that the performance indicators adopted meet the requirements laid out in Table 16, which lists the characteristics of good performance measures.

Table 16 - Characteristics of Good Performance Measurements

1.	Accurate and consistent
2.	Timely
3.	Enable targets to be set
4.	Identify problem areas
5.	Represent true cause and effect relationships
6.	Enable activities to be monitored
7.	Relevant to the objectives of organisation
8.	Visual indicators
9.	Understood by users
10.	Owned and supported by users

Blenkinsop and Burns[165,166] have identified the benefits of using a dynamic, iterative approach to the development of performance measurement systems in which the measurement system is derived directly from corporate strategy within the framework of the existing culture. This work identified that, in order to gain their commitment, those using the performance measurements should be consulted or allowed to participate in the setting up of the performance measurements. In this respect it was necessary to ensure that the overall goals of an organisation were known and understood by all involved and also how performance measures related to these goals. These needs were found to necessitate the requirement for 'two way' communications between levels in an organisation. Woodcock[157] identified the importance of identifying the common characteristics of a series of alternative internal measures which will support corporate external performance. He identified the common factors that influenced the degree of control which could be exerted on production as variability reduction, reduction in non-value adding complexity and improvements in management and worker competence. Kauth and Buker[159] have identified the performance measurements of use when implementing and operating MRP II systems. Here performance measurements are used to track performance and identify where corrective action is required such that resources can be focused in these areas. An essential element in the use of such performance measurements is the use of formal reviews in which the results of performance measurements are analysed, problem areas identified and responsibility for corrective action is assigned.

Chapter 5

5. Summary of Literature Search

5.1 Problems of Batch Manufacturing

In Chapter 1.0 it was identified that approximately 90% of all UK manufacturing companies are SME's with a high proportion of these operating in an irregular high variety / low volume batch manufacturing environment. The problems associated with the use of such batch manufacturing techniques were identified as difficulties in:

a. maintaining acceptable lead times,
b. maintaining reliable delivery dates, and
c. minimising manufacturing costs, this includes the problem of minimising quality related costs.

Within batch manufacturing industry there are many possible manufacturing and non-manufacturing related factors that give rise to the above problems, for example lack of sufficient capacity and failure to purchase materials on time. The current work focuses on shopfloor causes and categorises these according to the effects of 'queueing' and 'effectiveness of indirect services'. These two factors are considered to have a prime influence on the problems associated with batch manufacturing.

5.2 Queueing Effects

It is generally recognised that in batch manufacturing environments that queueing time represents the greater proportion of the total manufacturing lead time, Section 1.1.1. Hence, as queueing times increase so do lead times. In addition, queueing times also influence delivery reliability and manufacturing costs as follows.

1. Delivery reliability - The factors effecting delivery reliability have been identified as an inability to accurately estimate lead times and inability to maintain lead times, Section 1.1.1. Here the portion of lead times arising from processing times, set-up times and handling times would have little overall effect on the ability to maintain delivery reliability. Firstly, these times normally have to be estimated accurately in

order to provide standard times for the determination of direct costs. Secondly, although variability would exist within these times, they form only a minor part of the overall lead time. In this respect, the main problem area when attempting to maintain acceptable delivery reliability is the queueing time element of lead time which as stated forms the principal element of total manufacturing lead times. Because of the inability to generate detailed schedules in HV/LV environments (Section 3.6.3), queueing times within batch manufacturing environments are notoriously difficult to estimate and control, hence leading to uncertainty when determining appropriate delivery dates. It could be argued that by reducing queueing times that the variability associated with lead times would also decrease. However, this would depend on greater control being exercised over queueing times, i.e. control of queueing times rather then the reduction of queueing times is essential to reduce variability.

2. Manufacturing Costs - A significant proportion of manufacturing costs are incurred through the need to hold inventory and in particular the materials in-process on the shopfloor. Costs incurred through inventory are primarily in the form of interest charges on monies borrowed to finance stocks. Hence these costs are 'time based', i.e. the longer the time that materials remain on the shopfloor the greater will be the interest charges incurred. Hence queueing times have a direct effect on inventory costs since these determine the time over which interest charges will be incurred.

In summary, the main arguements for reducing queueing times, revolve around the benefits gained in the following areas:

1. Lead time is a major factor influencing the buying decision, hence reducing lead times improves the competitive advantage of an organisation.
2. Reducing lead times leads to less reliance on the need to forecast future demand and/or reductions in the time period over which forecasting must to performed. These changes lead to improvements in the accuracy of demand data obtained and hence improves the planning and control of the shopfloor and material resources.

3. Reducing lead times and improving the accuracy with which lead times can be estimated, assists in improving delivery reliability by enabling delivery dates to be achieved with greater consistency.
4. Reducing the time inventory is in-process leads to reductions in associated holding costs.
5. There is less chance of materials being damaged on the shopfloor hence reducing quality costs.

Queueing times can be considered to be a symptom rather then the cause of the problem itself. Hence it is necessary to identify the causes of queueing. In this respect, queueing is a function of processing batch size, the number of batches on the shopfloor and the sequence with which batches are processed at work centres, Section 1.1.1.

5.2.1 Batch Size

Within a HV/LV environment the arguements for increasing processing batch sizes are that handling costs are reduced and machine utilization is increased. Arguments for decreasing batch sizes are that inventory costs are reduced, quality problems become more obvious (Section 1.3.2) and queueing times are reduced. Overall it is considered more advantageous to reduce batch sizes and offset increases in handling costs by introducing plant layouts that reduce handling distances between work areas. In addition, the introduction of the OPT philosophy has highlighted the false economies of maximising the utilisation of non-bottleneck resources. Maximising the utilization of bottleneck resources can be better achieved, not necessarily by increasing the sizes of batches processed at bottlenecks, but by priority scheduling of these resources.

There is also an argument that suggests that lowering batch sizes will have little effect on queueing anyway. This is because in HV/LV environments processing batch sizes tend to be low, for example at RTH Ltd. approximately 70% of the batches processed contain less then 30 components. Hence, the effect of reducing batch sizes may not have a significant effect on reducing queueing times. However, optimum batch sizes need to be identified particularly with respect to the efficient use of bottleneck resources.

5.2.2 *Sequence*

The sequence with which batches are processed has been the subject of much research and is a major consideration in OPT (Section 3.6.1.3). Although a variety of dispatching rules have been developed, none can be said to possess universal advantages throughout the variety of batch manufacturing organisations that exist. OPT focuses on developing schedules that revolve around the need to maximise throughput through bottleneck operations. Hence, the techniques of forward and backward scheduling are used to determine the sequence batches are processed at non-bottleneck work centres.

The use of OPT scheduling procedures assists in reducing batch sizes, since a fundamental OPT principal is to match the capacity of non-bottleneck resources to that of the bottlenecks. This in effect leads to minimum batch sizes, that are compatible with bottleneck resources, being processed at non-bottlenecks. Although OPT has a beneficial effect in this way, implementing the technique relies on the use of complex scheduling computer software that requires for example, detailed feedback from the shopfloor, accurate data concerning process and set-up times and accurate forecasts of demand. In this respect, the use of OPT would generate similar problems to those that arise when using MRP, (Section 3.4), since this process also relies on the provision of accurate data.

5.2.3 *Number of Batches in Process*

As with batch size, there are alternative arguments concerning the number of batches that should be allowed on the shopfloor. Increasing the number of batches could create greater flexibility when coping with shopfloor based disruptions such as poor planning leading to lack of materials. In addition, improved machine utilization may result in particular on bottleneck machines and the increased variety in process improves the chances of being able to provide exactly what the customer wants. In support of reducing the number of batches allowed on the shopfloor, in any particular period, are that queueing times will decrease, inventory costs will fall, planning and control is less complex and stockturn ratios increase. Overall it is considered more advantageous to reduce the number of batches that are in-process simultaneously and to overcome problems that arise by more focused use of bottlenecks.

5.3 Effects of Indirect Services

Here the services of interest in the current research that directly effect the problems of batch manufacturing are production planning and control, quality management and control and the maintenance and servicing of processing equipment. Within batch manufacturing environments, the cost of providing these services is directly related to the effectiveness with which these services can be provided. Hence, when limited resources are available these service functions can directly effect leadtimes, delivery reliability and manufacturing costs.

1. Lead times - Here ineffective planning and control can lead to long lead times through such problems as poor scheduling, delayed expediting and the inability to co-ordinate manufacturing resources. Lack of effective quality management and control can extend lead times due to the production of defective items and the need for rework. Unreliable processing equipment arising from ineffective maintenance services can lead to delays in the processing of batches, hence extending lead times.
2. Delivery reliability - Here such problems as poor expediting, random machine breakdowns and quality problems can lead to difficulties in both estimating and maintaining lead times.
3. Manufacturing costs - Here poor plant layouts can lead to increased handling costs. Ineffective planning and control can lead to high inventory holding costs, and poor quality management and control lead to added quality related costs.

5.3 Contribution of JIT Techniques

Sections 5.1 and 5.2 have identified the basic changes that need to be implemented in order to improve lead times, delivery reliability and costs, i.e. reduce batch sizes, control the number of batches on the shopfloor, reduce indirect costs and reduce direct costs such as handling. The contribution that JIT can make to these objectives is as follows:

1. Reduce batch sizes and control the number of batches allowed onto the shopfloor. If batch sizes are reduced this would naturally lead to an increase in the number of batches that would be processed. Increasing the number of batches results in a more complex planning and control problem and results in the need for more indirect resources to plan and control production. Because kanbans are physical systems, they automatically control material flow hence helping to negate the need for more indirect planning and control resources. It is this aspect of kanbans that a HV/LV environment would need because of the large variety of batches normally processed.

Within JIT systems, continuous efforts are made to reduce batch sizes through reductions in set-up times, improving quality and improving equipment reliability. This type of effort can be performed as part of a wider continuous improvement philosophy and can receive direction and focus from the kanban control system.

2. Reduce the indirect costs associated with planning and control, quality functions and maintenance functions (Chapters 3 and 4). Indirect overhead costs within JIT systems are normally reduced by implementing changes in the working practices and shopfloor culture (Section 4.5). Here the main requirement is to enable direct shopfloor operatives to take on the tasks normally associated with indirect service functions. This enables greater effort to be placed in these areas which are essential to support reductions in batch sizes.

3. Reduce handling costs by reducing handling distances and/or reducing the number of load movements by increasing the size of loads. Adopting a product based plant layout is normally the primary method of reducing handling costs since this enables work centres to be placed such that handling distances are minimised (Section 2.2). Kanban quantities and container sizes also influence handling costs.

5.4 JIT Requirements for HV/LV Environments

Section 5.3 has identified that JIT environments are capable of addressing the basic types of problems that are of concern within batch manufacturing environments. It is, therefore, necessary to examine the potential for implementing JIT techniques within such environments.

Essential elements for the successful implementation and operation of a JIT environment are a suitable product based plant layout and material control using kanban signals. These two elements are instrumental in promoting the benefits of JIT (Section 2.1) and focusing continuous improvement activities.

5.4.1 Product Based Layouts

The efficient operation of JIT requires the adoption of product based plant layouts in which facilities are arranged according to the needs of products and in the same sequence as the operations necessary for manufacture of the components.

The requirements that such layouts must provide can be identified. These can be categorised according to whether the requirement is specifically needed for the HV/LV JIT environment to operate (i.e. **key requirement**) or is a **universal requirement** that is appropriate to both JIT in HV/LV environments, traditional JIT environments and process based environments.

Requirement classifications have been listed in Table 17. Suitable solutions to the plant layout problem for HV/LV JIT environments must enable these requirements to be achieved.

Table 17 - Requirements of HV/LV JIT Plant Layout

Requirement	High variety/low volume
Provide a series of production stages that do not break precedence constraints	Key requirement
Allow materials to flow in one direction, i.e. provide visible material flows	Key requirement
Provide sufficient process capacity	Key requirement
Be able to cope with the variety of components requiring processing	Key requirement
Provide shopfloor interprocess kanban stores	Key requirement
Minimise material handling	Universal requirement
Provide no areas where excess inventory can build up	Universal requirement
Provide areas for other machine resources, such as tools, jigs and fixtures	Universal requirement
Allow greater standardisation of processing procedures	Universal requirement
Allow 'ownership', for a family of components to rest with a team of operators	Universal requirement
Utilise the flexibility and multiskills of operators	Universal requirement
Encourage teamwork	Universal requirement
Minimise material handling distances	Universal requirement
Minimise space requirements	Universal requirement
Improve communications	Universal requirement
Focus on quality by reducing feedback time	Universal requirement
Reduce the variety of components that need to be processed	Universal requirement, however, variety of components is an unavoidable feature of this environment

The implementation flow manufacturing has traditionally been through the use of GT and cellular manufacture. GT techniques have been identified as bringing significant benefits when implemented in batch manufacturing environments (Section 2.2.1).

In HV/LV manufacturing environments, however, the potential for using GT and cellular manufacturing techniques has been found to be limited as specified in Section 2.2.2. Essentially the main limitation of GT is that is not always possible to identify groups of components from which to form effective cells that can fully process all the components assigned to them.

5.4.2 Material Control

JIT requires that kanban material controls (Section 2.3) are implemented, the requirements of which are listed in Table 18.

Table 18 - Requirements of HV/LV Kanban Controls

Requirement	High variety/low volume
Visible signals control material flow	Key requirement
Containers physically limit WIP	Key requirement
Allow materials to enter system at various stages	Key requirement
Allow finished components to be delivered from the end of the production line	Key requirement
Be able to cope with the variety of components requiring processing	Key requirement
Enable identification of bottlenecks	Key requirement
Standard containers must enable direct transfer of parts between successive workstations to take place	Key requirement
a stable 'master production schedule' so fluctuations in demand can only be handled by adding or removing containers and kanban cards	Key requirement
Additional involvement required by workers in handling materials due to the frequent movement of containers	Key requirement
Strict operational discipline in the use of kanbans	Key requirement
Provide no areas where excess inventory can build up	Universal requirement
Minimise material handling	Universal requirement
Operator involvement	Universal requirement
Correct quantities and part types moved at the right time	Universal requirement
The final operation controls the entire manufacturing system	Final operation often changes making this difficult
Synchronised material flow	Synchronisation difficult

1. Kanban systems have limitations, (Section 2.3.9), which are often exacerbated in HV/LV environments, pull system variants have been developed, Section 2.4, however none of these variants operate effectively in HV/LV environments

5.4.3 JIT Infrastructure

JIT also requires an infrastructure that will allow continuous improvement exercises to be carried out. The requirements of such infrastructures are listed in Table 19 and are of a universal nature.

Table 19 - Requirements of a JIT Infrastructure

Requirement	**High variety/low volume**
Improve operator commitment to quality.	Universal requirement
Reduce machine set-up times.	Universal requirement
Increase job standardisation.	Universal requirement
Improve the processing consistency of machines.	Universal requirement
Improve machine reliability.	Universal requirement
Reduce machine repair times.	Universal requirement
Reduce work-in-progress levels.	Universal requirement
Improve product designs.	Universal requirement
Improve control over suppliers quality and delivery performance.	Universal requirement
Increase parts standardisation.	Universal requirement
Continuously improve all areas of production	Universal requirement

Chapter 6

6. Process Sequence Cell Layouts (PSCL's)

6.1 Development of the PSCL methodology

The PSCL methodology was developed as a result of attempts to design suitable plant layouts at Rank Taylor Hobson Ltd. Initially the operation routings for the range of components were loaded into the Microsoft Excel spreadsheet package to allow data sorting procedures to be utilised. The first attempts to identify suitable GT based cells were unsuccessful as were RTH's own attempts to create cells that could process families of parts. The results of RTH's attempts are shown is Section 6.4

In further attempts process routes were sorted according to the 'number of operations' required. Analysis of this data revealed a Pareto relationship between 'number of operations' and the cumulative percentage of parts, i.e. it was found that the majority of the components required only two operations and a relatively small percentage required greater than 5 operations. Attempts were then made to form cells using the 'number of operations' characteristic by grouping those machines required to perform operations on 2-operation components. However, this method proved ineffective since no visible material flow through the plant layout could be achieved.

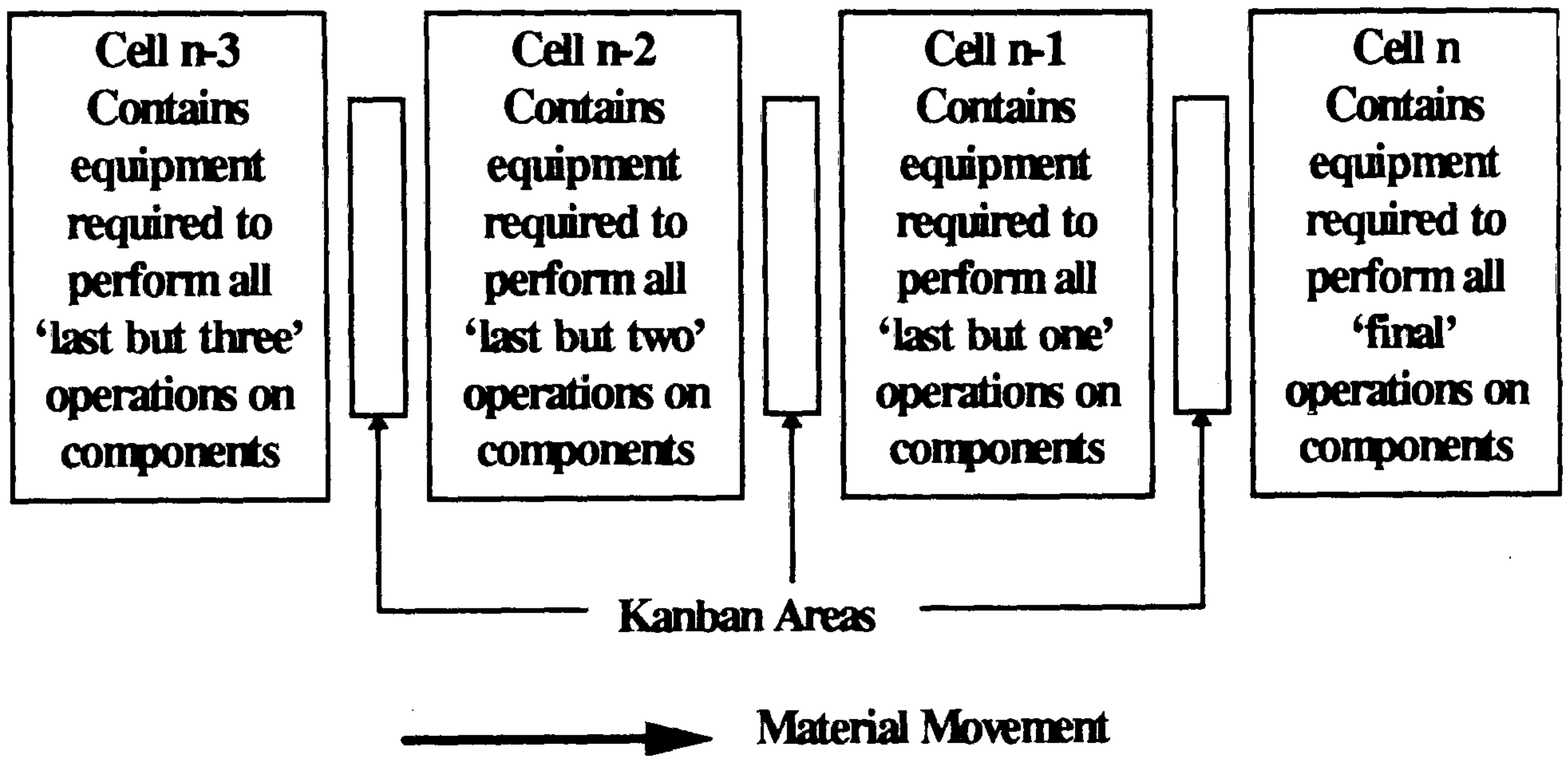
A component characteristic was identified when analysing operation data was that certain machines tended to appear in the first operations of the routings. The data was then right justified, i.e. the last operations of each component routing was placed in the right hand column of the spreadsheet, to determine if certain machines tended to be the latter operations of the process routes. The right justified data confirmed this fact and the basic principles of process sequence cell layouts began to form.

Initially cells were formed using only right justified data and with low levels of component variability this method was successful at identifying distinct groups. However at higher levels of component variety the basic method of identifying cells had to be extended to include not only right justified data but also left justified and centre justified data. A description of the final method adapted is described in Section 6.2.

6.2 Process Sequence Cell Layouts

A process sequence cell layout, (PSCL), is composed of individual cells each of which contains a number of items of processing equipment. Each cell represents an individual stage in the processing routes of all components processed within a manufacturing area or company. Ideally, therefore, processing equipment is allocated to an individual cell depending on the cell's position within the operation route of components as shown in Figure 8.

Figure 8 - Theoretical Layout of a Process Sequence Cell



Trials were carried out to determine a suitable methodology for allocating individual items of processing equipment to specific cells. The results of these trials enabled the identification of process sequence cell layouts to be accomplished without the need for complex algorithms or coding systems as would be necessary when allocating individual machines to group technology cells (Section 2.2.1). In terms of the PSCL designed for the case study organisation items of processing equipment have been allocated to process sequence cells using the editing and sorting facilities available in a commercial spreadsheet package, i.e. Microsoft Excel.

6.3 Designing PSCL's

6.3.1 Allocation of Equipment to Cell

The decision to use a spreadsheet package in the design of PSCL's is primarily based on the ease with which such systems manipulate data and the availability of data sorting facilities. Such facilities are essential, since large amounts of production data are generated in HV/LV manufacturing environments. For example, the case study organisation used within the present research has approximately 20,000 lines of information for the components manufactured.

In order to demonstrate how PSCL's are identified, a small sample of data has been created to represent a typical section of a part routing list, i.e. Table 20, in which it can be seen that the number and types of processing equipment required differs between components.

Table 20 - List of Operation Routes

Part P01	A	B	C	D
No. of Cpts	10	10	10	10
Part P02	B	D		
No. of Cpts	100	100		
Part P03	B	A	C	
No. of Cpts	70	70	70	
Part P04	A	E	B	
No. of Cpts	90	90	90	
Part P05	B	C	D	E
No. of Cpts	130	130	130	130
Part P06	A	B		
No. of Cpts	100	100		
Part P07	C	E		
No. of Cpts	10	10		
	A,B,C,D and E are processing equipment codes			

6.3.2 Data Justification Techniques

The design of PSCL's uses various justification methods to sort data, (i.e. data along spreadsheet rows), in order to be able to select the most appropriate machines to place in each cell. Justification requires aligning the data with respect to either the left, right or centre columns of those columns that contain the operation routes. These procedures are described in detail in Sections 6.3.3 - 6.3.5.

The spreadsheet package can be used to determine the total number of components required for each item of equipment, at each operation stage. For example, with respect to machine A, in Table 20 it can be seen that machine A is used to perform the first operations on components P01, P04 and P06. The spreadsheet package, therefore calculates the total number of P01, P04 and P06 components processed by Machine A.

6.3.3 Right Justification

The sorting facilities of the spreadsheet package are initially used to group components in terms of the number of operations required. Then editing facilities are used to move blocks of process routes until last operation codes are aligned in the far right hand column (the end column) and last but one operations are placed in the penultimate column (end column -1) The resulting right justified data is shown in Table 21.

Table 21 - 'Right Justified' Process Routes

	End Column -3	End Column -2	End Column -1	End Column
Part Code	Last but 3 Operation	Last but 2 Operation	Last but 1 Operation	Last Operation
P01	A	B	C	D
P02			B	D
P03		B	A	C
P04		A	E	B
P05	B	C	D	E
P06			A	B
P07			C	E

Combining information from Table 20 and Table 21 enables the 'total number of components processed per machine' within each operation stage to be determined as shown in Table 22.

Table 22 - Total Components Processed for 'Right Justified' Process Routes

	Cell 1	Cell 2	Cell 3	Cell 4
Equipment Code	Last but 3 Operation	Last but 2 Operation	Last but 1 Operation	Last Operation
A	10	90	170	
B	130	80	100	190
C		130	20	70
D			130	110
E			10	140

6.3.4 Left Justification

When generating this data table, the sorting facilities of the spreadsheet package are used to left justify each individual process route using the same technique described in Section 6.3.3 but placing all the first operation machine codes in the far left column, i.e. termed column 1. The resulting left justified data is shown in Table 23.

Table 23 - 'Left Justified' Process Routes

	1st Column	2nd Column	3rd Column	4th Column
Part Code	First Operation	Second Operation	Third Operation	Fourth Operation
P01	A	B	C	D
P02	B	D		
P03	B	A	C	
P04	A	E	B	
P05	B	C	D	E
P06	A	B		
P07	C	E		

Using information from Table 20 and Table 23 enables the 'total number of components processed per machine' at each operation stage to be determined as shown in Table 24.

Table 24 - Total Components Processed for 'Left Justified' Process Routes

	Cell 1	Cell 2	Cell 3	Cell 4
Equipment Code	First Operation	Second Operation	Third Operation	Fourth Operation
A	200	70		
B	400	110	90	
C	10	130	80	
D		100	130	10
E		100		130

6.3.5 Centre Justification

The sorting facilities of the spreadsheet package were used to centre justify each individual process route, as illustrated in Table 25. The centre cell on the spreadsheet is based on the half way point of the longest part routing (e.g. if the longest route had eleven stages the centre would be cell six, if it were eight stages the centre would be between cells four and five). When the longest routing is an odd number, the routings with even numbers of stages cannot be centred exactly, making the positioning biased either to the left or the right. This is overcome by 'staggering' alternate process routes that have an even number of stages. The converse is also true when the longest routing is an even number. Staggering is demonstrated in Table 25 in the routings for P03 and P04. Here the component with the longest routing has 4 operations. The centre cell will, therefore, lie between cells 2 and 3. The routing for component P03 is, therefore, 'staggered' to the right, i.e. its centre operation is placed in column 3. Component P04 is 'staggered' to the left, i.e. its centre operation is placed in column 2.

Table 25 - 'Centre Justified' Process Routes

Equipment Code	Centre -1 Operation	Centre Operation	Centre +1 Operation	Centre +2 Operation
P01	A	B	C	D
P02		B	D	
P03		B	A	C
P04	A	E	B	
P05	B	C	D	E
P06		A	B	
P07		C	E	

Using information from Table 20 and Table 25 enables the 'total number of components processed per machine' to be determined as shown in Table 26.

Table 26 - Total Components Processed for Centre Justified Process Routes

	Cell 1	Cell 2	Cell 3	Cell 4
Equipment Code	Centre -1 Operation	Centre Operation	Centre +1 Operation	Centre +2 Operation
A	100	100	70	
B	130	180	190	
C		140	10	70
D			230	10
E		90	10	130

6.3.6 Allocation of Equipment

In this example the number of items of each type of processing equipment that need to be allocated are shown in Table 27.

Table 27 - Number of Available Facilities

Machine / Facility	Number of Facilities
A	2
B	3
C	2
D	1
E	1

The right, left and centre justified tables (Table 22, Table 24 and Table 26) are used to identify the most appropriate cell to place each item of processing equipment in the following manner:

For machine A, examine Table 22, 24 and 26 in sequence and locate the cell that would process the highest number of components. The information shown in Table 28 is extracted from Table 22, 24 and 26.

Table 28 - Processing Data for Machine A

Table	Cell Number	Number of Cpts Processed
22	1	10
	2	90
	3	170
24	1	200
	2	70
26	1	100
	2	100
	3	70

From Table 28 it can be seen that cell 1 (Table 24) processes the greatest number of components (i.e. 200 components) and cell 3 (Table 22) the second largest number of components (i.e. 170 components). Since there are two type A machines, the first would be allocated to cell 1 and the second allocated to cell 3. This procedure is then repeated for all other items of equipment. For example, in terms of machine B there are three items of processing equipment. The three cells processing the largest number of components are cell 1 (i.e. 400 components, Table 24), cell 4 (i.e. 190 components, Table 22), and cell 3 (i.e. 190 components, Table 26).

Using this methodology the allocation for the equipment in this example is shown in Table 29.

Table 29 - Allocation of Equipment to Cells

Cell 1	Cell 2	Cell 3	Cell 4
A	C	A	B
B	C	B	E
		D	

6.3.7 Cell Amalgamation

The next stage in the PSCL design process is to examine the potential for the amalgamation of cells identified in the initial cell design. This involves combining within a single cell the equipment contained in adjacent cells, in order to:

a. smooth capacity requirements of each cell,
b. reduce the total number of cells and consequently the number of cell supervisors, and
c. increase the number of machines in each cell in order to create an environment that would enable the full benefits of cellular manufacture to be gained.

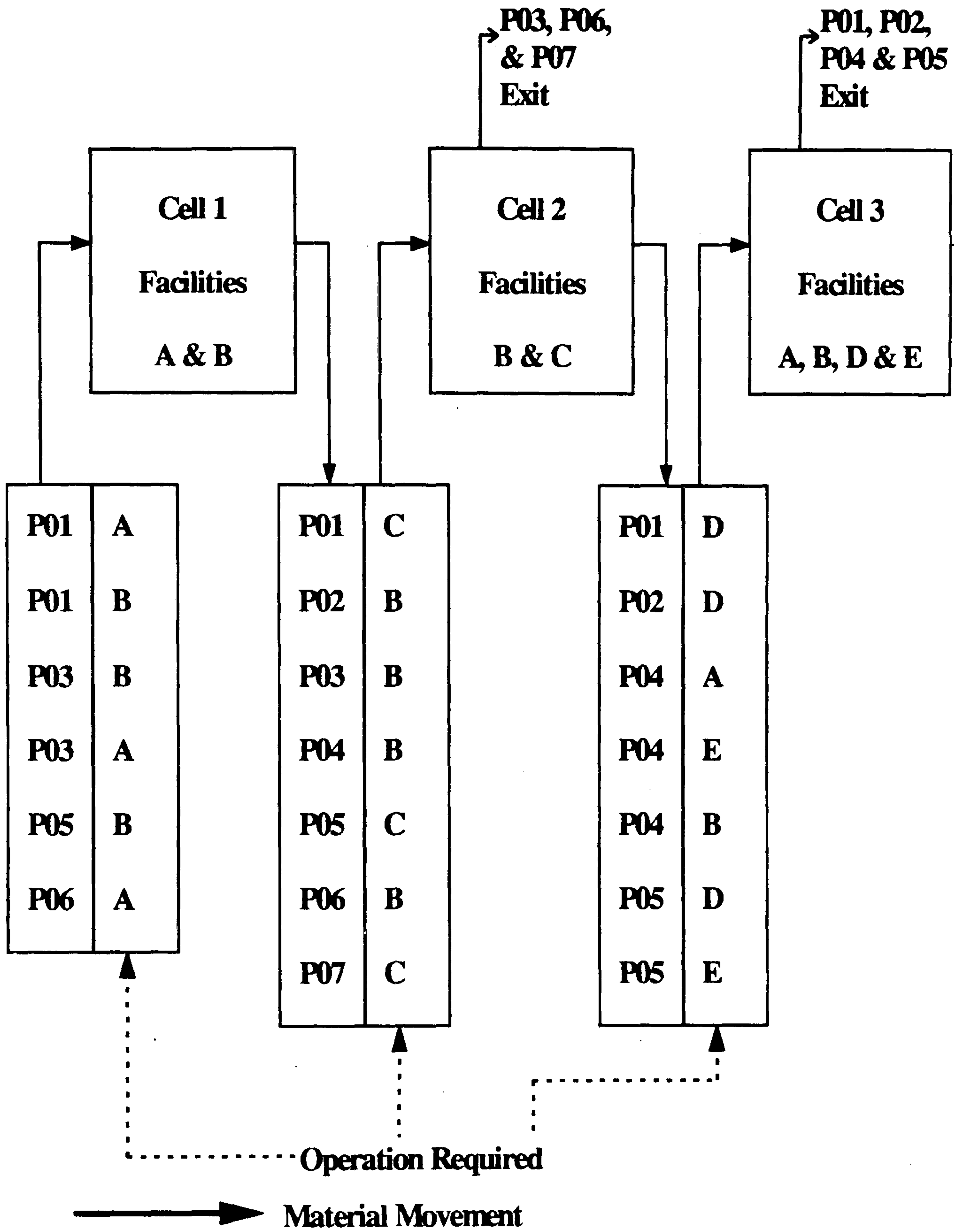
In the example used, 9 items of equipment have finally been allocated to three cells by amalgamating cells 2 and 3, and cells 3 and 4 as shown in Table 30.

Table 30 - Amalgamated Cells

Cell 1	Cell 2	Cell 3
A	B	A
B	C	B
	C	D
		E

Figure 9 illustrates the layout of the cells shown in Table 30 and the components each cell will process. Materials would move from one cell to the next making material flows visible and making possible the introduction of kanban controls between cells.

Figure 9 - Layout of Example PSCL



6.4 Case Study - RTH Limited

RTH Ltd. manufacture a wide range of high precision metrology equipment using a variety of processing equipment, as shown in Table 31.

Table 31 - Company Information

Number of Product Types	34
Number of Machined Part types	950
Number of Items of Processing Equipment	41
Number of Parts types x Number of each part required per year	19736
Batch Sizes	Min. =1 Avg. = 30 Max. = 200

In order to improve shopfloor efficiency the following areas were identified, i.e.:[167]

a. improve effectiveness,
b. improve product lead times,
c. improve stock turns,
d. improve value added content,
e. improve operator flexibility,
f. improve customer satisfaction, and
g. improve communications.

In order to achieve these aims it was decided to reorganise the non-assembly processing areas into manufacturing cells.

The GT analysis carried out grouped the parts into families based on similarity of geometric shape, i.e. cylindrical or flat. The possibility of distinct sections of the shopfloor, dedicated to manufacturing flat components and cylindrical components, was then examined which resulted in the identification of seven cells. However the analysis of the feasibility of adopting these cells (Table 32) indicated that:

a. there were insufficient machines to implement each cell, and

b. each cell could only process a limited number of parts.

Table 32 - Results of GT Feasibility Study[167]

Cell Number	% of Components not fully Processed
1	45
2	25
3	25
4	24
5	22
6	21
7	10

A typical sample of the process routings for the parts manufactured by RTH Ltd. are shown in Table 33.

Table 33 - Sample of Process Routings for RTH Ltd

Part Code	Operation 1	Operation 2	Operation 3	Operation 4	Operation 5	Operation 6	Operation 7
H45/24	32011	30222	33521	30517	33011	33521	30221
H45/25	32011	30221	33521	30517	33011	33521	30221
H45/3	39911	34257					
H45/3301	31011	31151					
H45/3303	31251						
H45/3304	39912	39931	31021	30221			
H45/3305	39912	39931	31021				
H45/3357	31251	30221	34257				
H45/3389	31241	39931					
H45/3432	31021	33011	31111	34256			
H45/3436	39912	39931	31021	39949			
H45/3445	31021						
H45/3447	31231	33521	30221				
H45/3450	31011	33521	32011	30221			
H45/3452	31021	33011	39943				

The component routing data from RTH Ltd. was entered into the spreadsheet package Initially the process routes, i.e. equipment codes only, for all components processed by the case study manufacturing organisation were downloaded from the MRP database into the spreadsheet package. and was right, left and centre justified as described in Section 6.3.2, and is shown in, Table 34, Table 35 and Table 36.

Table 34 - Total Parts Processed for Right Justified Routes

M/C Code	Last -9	Last -8	Last -7	Last -6	Last -5	Last -4	Last -3	Last -2	Last -1	Last
30211		10		10		30	142	80	155	170
30213				50		65	109	712	341	2
30222						73	81	240	152	15
30512						9	15	18	28	40
30513								13	15	5
30514									40	208
30515							6	10	10	50
30516								135	660	70
30517						16	60	273	781	1451
30518		8	10	12		28	41	70	173	
31021		55	50	12	45	150	172	921	1523	126
31041		6			13	147	212	348	372	15
31061			3	7	36	296	292	631	331	20
31111				3	17	13	100	166	561	417
31112					9	8	25	29	133	60
31131								15	103	150
31151			16	5		55	215	236	500	783
31231	8		8		14	16	132	363	330	217
31232					12		25	38	224	98
31241						10	10	245	1382	19
31251			18		9	8	245	712	1335	225
31914							16	62	40	307
31931							20	92	245	464
31941						5		91	131	209
32011				107	157	446	966	2139	5066	2725
32013					12		54	288	854	760
32021						42	29	116	182	317
32911						20	38	8	381	723
33011			45	61	5	78	338	686	2913	6964
33021									96	31
33521				20	60	31	230	539	679	3087

Table 35 - Total Parts Processed for Left Justified Routes

M/C Code	First	First +1	First +2	First +3	First +4	First +5	First +6	First +7	First +8	First +9
30211	383	139	15	20		15	50			
30213	1265	14								
30222	244	280	36	11						
30512	72	38	10							
30513			28	5						
30514		123	105	20						
30515			30	20	20	6				
30516		669	135	51	10					
30517	228	1130	663	279	210	45	32			
30518	12	321	5	12		8				
31021	2526	310	59	144	21	12				
31041	1051	20	34		8					
31061	1516	47	35		10		8			
31111	132	480	337	226	68	5	29			
31112	89	163	10			2				
31131	23	10	65	80	70	10		10		
31151	204	1110	347	35	60	30		6	10	8
31231	770	100	195	15		8				
31232	257	132	8							
31241	1647		10			9				
31251	2243	70	251							
31914		277	115	18	15					
31931	274	438	107	10						
31941	42	168	101	105	20					
32011	5604	4048	1034	625	235	25	5	10		
32013	477	740	469	138	20	18	98	8		
32021	109	267	178	57	30					
32911	77	799	159	121	14					
33011	239	6267	3243	834	288	60	30	95	24	
33021	15	26	86							
33521	192	1550	1406	759	437	211	25	21	45	

Table 36 - Total Parts Processed for Centre Justified Routes

M/C Code	Cent -4	Cent -3	Cent -2	Cent -1	Cent	Cent +1	Cent +2	Cent +3	Cent +4	Cent +5
30211		10	35	153	204	135	20	15	50	
30213			50	174	1041	14				
30222			10	124	320	96	21			
30512				34	46	30	10			
30513						28	5			
30514						143	105			
30515						20	36	20		
30516					27	780	58			
30517				16	465	1149	704	221	32	
30518		8	22	36	99	193				
31021		105	12	258	2304	276	105	12		
31041		6	5	350	727	10	15			
31061		3	43	545	980	17	18	10		
31111			3	64	197	541	398	58	16	
31112			9	13	87	153		2		
31131					23	35	120	80	10	
31151			21	55	564	706	365	75	6	
31231	8		22	122	652	167	109	8		
31232			12	25	220	132	8			
31241				20	1627		10	9		
31251		18	9	265	1951	106	215			
31914					38	289	83	15		
31931				5	292	442	90			
31941				5	42	239	130	20		
32011			101	1099	5660	3580	1016	140	10	
32013				12	499	965	366	124	2	
32021				54	147	293	187	5		
32911				20	105	781	250	14		
33011			90	55	811	6952	2823	218	125	
33021					15	102	10			
33521			20	81	593	1362	1999	510	36	45

The number of items of processing equipment available for allocation in the PSCL are shown in Table 37.

Table 37 - Number of Items of Equipment for RTH Ltd

Equipment Code	Number of Items	Equipment Code	Number of Items	Equipment Code	Number of Items
30211	1	31021	3	31914	1
30213	1	31041	1	31931	1
30222	1	31061	1	31941	1
30512	1	31111	1	32011	4
30513	1	31112	1	32013	1
30514	1	31131	1	32021	1
30515	1	31151	3	32911	1
30516	1	31231	1	33011	4
30517	3	31241	1	33021	1
30518	1	31251	3	33521	3

Using the procedures described in Section 6.3.6 the equipment was allocated to cells as shown in Table 38. Amalgamation of the cells produced the results shown in Table 39.

Table 38 - Equipment Allocation for RTH Ltd

M/C Code	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8	Cell 9	Cell 10
30211	X									
30213	X									
30222					X					
30512	X									
30513			X							
30514										X
30515										X
30516						X				
30517		X				X				X
30518		X								
31021	X				X				X	
31041	X									
31061	X									
31111									X	
31112		X								
31131										X
31151		X				X				X
31231	X									
31232	X									
31241	X									
31251	X				X				X	
31914										X
31931										X
31941						X				
32011	X	X			X				X	
32013						X				
32021										X
32911		X								
33011		X	X			X				X
33021						X				
33521		X					X			X

Table 39 - Amalgamated Cells for RTH Ltd

Cell 1	Cell 2	Cell 3	Cell 4	Cell 5
30211	30517	30222	30516	30514
30213	30518	30513	30517	30515
30512	31112	31021	31021	50517
31021	31151	31151	31111	31131
31041	31232	31251	31251	31151
31061	31241	31941	31931	31914
31231	32011	32011	32011	32021
31251	32911	32013	33011	33011
32011	33011	33011	33521	33521
		33521		

6.4.1 Static Analysis

Upon analysing the material movements of the PSCL shown in Table 39, in which 950 components were used in the design, it was found that:

1. 80.9% of all material movements would occur in a forward direction between adjacent cells in the layout.
2. 10.6% of material movements would occur in a forward direction between non-adjacent cells.
3. 8.5% of material movements require components to have one movement in a backwards direction through the cell sequence.

Of the estimated 19,736 parts, analysis of material movement proved that:

1. 84.1% of all material movements would occur in a forward direction between adjacent cells in the layout.
2. 11.1% of material movements would occur in a forward direction between non-adjacent cells.
3. 4.8% of material movements require components to have one movement in a backwards direction through the cell sequence.

6.4.2 Achievement of Key Requirements

1. Provide a sequence of production stages - Each cell within the PSCL design represents a stage in the processing sequence of components.
2. Provide materials flow in one direction - 95.2% of components move in a forward direction between cells.
3. Provide sufficient capacity - each cell can be designed using the processing capacity requirements of components to ensure this key requirement is achieved.
4. Provide sites for kanban in-process areas - equipment may be placed on the shopfloor such that areas are provided for kanban containers.
5. Provide environment for JIT infrastructure - each cell within the PSCL could be self contained allowing local control by operators and therefore a suitable environment for operators to work as a team.

PAGE

NUMBERING

AS ORIGINAL

7. Dynamic Analysis of PSCL's

7.1 Introduction

Chapter 5 has provided a description of the design of PSCL's in terms of the number of cells and items of processing equipment allocated to each cell. Analysis of the static features of PSCL's indicates that 95.2% of components move in a forwards direction. Although the majority of material movements take place in a forwards direction, because the dynamics of material movement is radically different to existing forms of plant layout it is necessary to identify the operational behaviour of PSCL's when processing is taking place. In this respect, computer simulation has been used as a tool for accomplishing this task. There are a number of commercial computer simulation packages currently available all of which have the facilities for modeling PSCL's including ProModel[168] which was selected based on its availability and ease with which models could be constructed.

7.2 Objectives of Simulation

The objectives of the simulation exercise is to study the operational behaviour of a PSCL in order to gain insights into its dynamic characteristics. Of interest is the behaviour of the material flows between cells under alternative conditions, namely varying levels of component variety and alternative batch sizes. From the simulation study it should also be possible to observe the effects of PSCL's on the queueing characteristics of batches, the impact of queueing on component lead times and identify the criteria that determine the lead time of components through the system.

The simulation model should also assist in determining whether kanban controls could successfully be used and assist in identifying the variables that should be used to determine the form that such kanbans should take.

7.3 Data Collection and Model Building

The simulation model was developed using case study data obtained from Rank Taylor Hobson Ltd. Two basic types of parameters have been used to build the model, i.e. fixed parameters, the values of which do not alter during simulation runs, and variable parameters whose values are represented in the main by probability distributions selected after consultation with RTH Ltd. production management.

7.3.1 Fixed Parameters

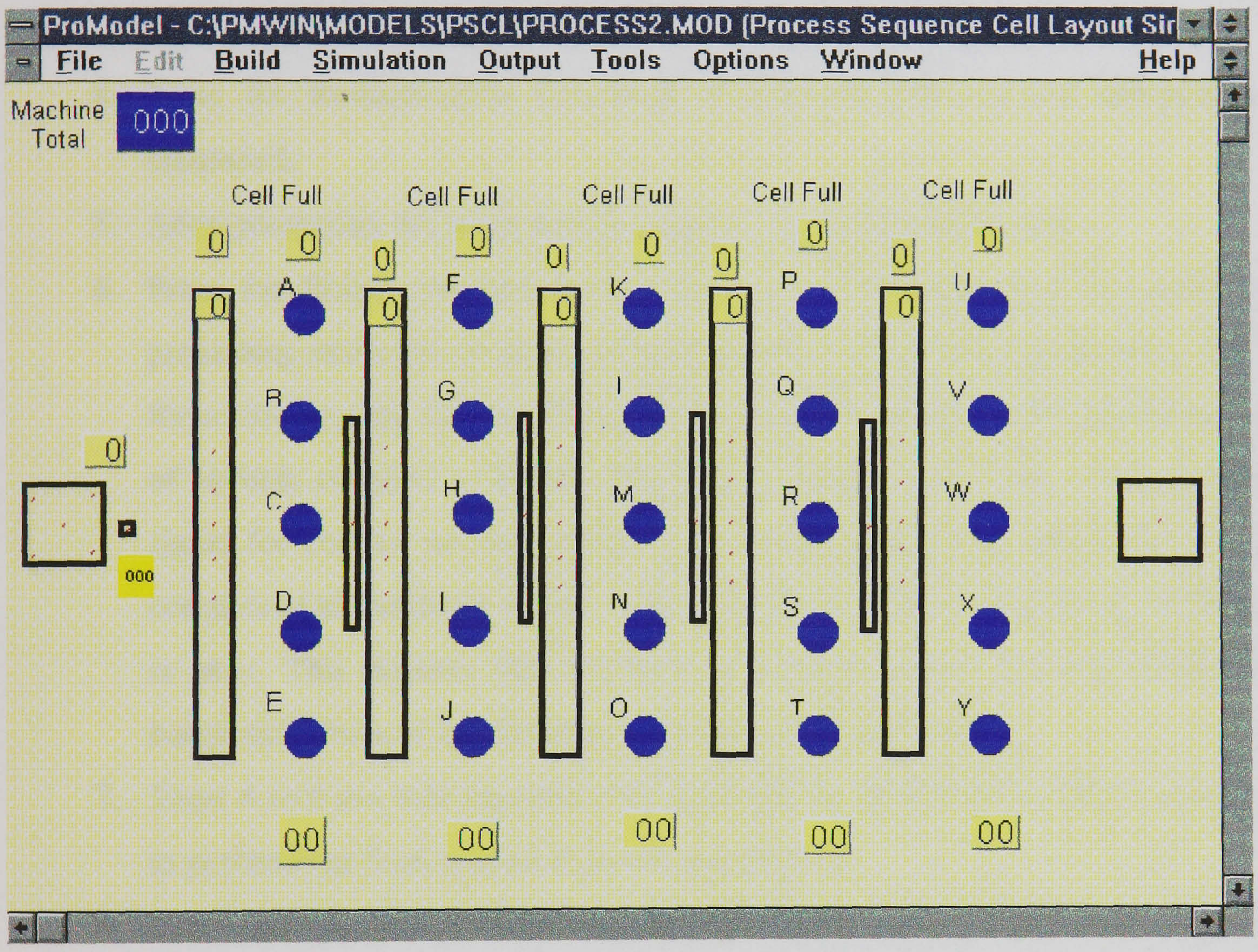
The main items of processing equipment used within RTH Ltd. were identified and represented as fixed parameters within the model. The PSCL model developed, therefore, contains 25 machine locations. This equipment is allocated to five process sequence cells as shown in Figure 10 with the cell performing **first operations** containing Machines A to E and the cell performing **final operations** containing Machines U to Y.

The model also has fixed data parameters that provide the essential elements used to move materials through the processing cells, i.e.:

1. An **arrival point**, where all batches of components arriving into the system are initially generated. From this point the batches are conveyed to the following **waiting point**.
2. A **waiting point**, from which each batch is moved to the **kanban area** that precedes the processing cell used to perform the component's first operation, i.e. in the majority of cases this will be Cell 1. The capacity parameter of the waiting point is also used to control processing batch sizes.
3. **Kanban areas** located in front of each processing cell where batches are placed prior to release to the succeeding processing cell.
4. **Finish areas** located after each processing cell where batches are conveyed directly after processing. From these finish areas, each batch is moved to the **kanban area** that precedes the cell required to perform the next operation on the batch.

5. An **exit point**, which is located directly after the final process cell and receives all batches that have completed processing. This **exit point** receives batches directly from the processing cell used to perform the final operation on a specific batch. From the **exit point**, batches move out of the system.

Figure 10 - Graphical Representation of PSCL



The paths along which the components travel through the model needed to be specified to provide the model with information about how batches move between the above locations. As the PSCL is a theoretical model, the data for these paths was based on how the paths would be expected to operate in a real situation. In order to identify these paths and the rules required to move materials between cells, a manual simulation was performed. This simulation employed only two cells and a random sample of batch types. The simulation was used only to identify material paths and control rules. It was recognised that attempting to use the manual simulation to perform a more detailed analysis of a PSCL environment would be time consuming and error prone, hence the decision to use computer simulation tools.

From the manual simulation it was identified that for each batch processed, material movement through the model should take place as follows:

1. The batch is initially generated at the **arrival point**.
2. From the **arrival point** the batch moves to the **waiting point**.
3. From the **waiting point** the batch moves to the **kanban area** preceding the processing cell that performs the first operation on the components.
4. From the **kanban area** the batch moves into the cell and components are processed.
5. After processing the batch moves into the succeeding **finish area**.
6. From the **finish area** the batch moves to the **kanban area** that precedes the processing cell used to perform the next operation on the components. The rules for controlling the flow of entities through the model are initiated using the values of variable counters at specific locations throughout the model. For example, the signal for entities to enter kanban areas is actioned only when the sum of the contents of all machines within a cell is zero and the sum of the contents of all cells is zero. This ensures that materials only move when the cell containing the bottleneck resource has finished processing its components.
7. Steps 4 to 6 are then repeated until the batch is finished processed at the cell used to perform the final operation on the components.
8. From the cell that performs the last operation on the components, the batch is moved to the **exit point** and from there out of the system.

The above areas have fixed capacities associated with them, i.e.:

a. all processing equipment has a capacity of 1, and
b. other locations have capacities between 20 and 30000 since they are designed to hold batches or groups of different part types. In order to examine the influence of batch size on the operation of a PSCL system, models have been constructed using batch sizes of 20 and 40.

Further fixed parameters included within the model are the components that are processed. Here the large number of components processed within RTH Ltd. had to be reduced in order to reduce the effort and time required for model building. In order to satisfy the objectives of the simulation exercise, therefore, it was necessary to obtain a representative sample of the total parts processed by RTH Ltd. This was achieved by initially identifying all unique process route types and the number of components requiring each route type. This resulted in entities being selected with 41 unique process route types, i.e. these were representative of the total process routes. In order to determine the influence of part variety on the operation of a PSCL, models were constructed using 41, 30 and 20 part types. The components and their routings are shown in Table 40.

Table 40 - Part Routings of ProModel Simulation

Part Number	Operation 1	Operation 2	Operation 3	Operation 4	Operation 5
A	A	F	K	P	U
B	B	G	L	Q	V
C	C	H	M	R	W
D	D	I	N	S	X
E	E	J	O	T	Y
F	A	G	M	S	Y
G	B	H	N	T	U
H	C	I	O	P	V
I	D	J	K	Q	W
J	E	F	O	R	X
K	E	I	N	Q	U
L	D	H		P	Y
M	C	G	O	T	X
N	B	F		S	W
O	A	J		R	V
P	B			S	U
Q		I		P	Y
R	D	H		P	U
S	E			R	V
T	A	F			X
U	D	G	L		W
V			N	Q	U
W	E	J	N		V
X	B	I		T	U
Y		F		S	Y
Z				Q	U
1		J	L		
2	B	F			
3			K	R	
4				T	Y
5	E	G			
6			L	T	
7				P	W
8		I	N		
9	D	J			
10		F	L	P	
11				S	V
12		H	O		
13	C		N		
14				T	U
15		I	M		X

7.3.2 Variable parameters

The variable parameters of the system are the processing times for each component type at each item of processing equipment and the movement times for transporting the components between locations in the model. Here experienced personnel from RTH

Ltd. aided in the building of the model by providing representative times. In addition, each equipment location has associated with it a downtime that results from set-up procedures when changing between part types.

The arrival of components into the PSCL model had to be representative of the existing components processed and yet ensure that the parts arrive at random intervals. The arrivals were calculated depended upon the route sizes, (i.e. in terms of the number of operations per route), as listed in Table 41.

Table 41 - Frequency of Operations in Process Routes

Number of Operations in Process Route	Frequency (%)
2	47%
3	29%
4	12%
5 or more	12%

The variation in frequency values shown in Table 41 are represented in the arrivals section as the 'time between arrivals' (TBA) i.e. a value which must be input for each entity. In this respect the TBA for the '2-operation' routes is less then the TBA for '5-operation' routes. TBA values are determined by multiplying the 'number of routings with a specific number of operations' by the corresponding percentage from Table 41. The inverse of the resulting value was then calculated in order to represent the TBA.

To alter the number of component types entering the system, i.e. for use with other simulation runs, a simple yes/no toggle is available within ProModel that can be used to specify whether a specific part type can enter the system.

The PSCL models employ 52 variables for recording the state of various elements of the model, (e.g. the number of components in kanban areas or cells), and for decision making. The basic functions of these variables are as follows:

a. to record the quantities of entities within cells,

b. to control the flow of entities through the model, i.e. the use of variables rather than the numerous built-in rules of ProModel was necessary due to the unique attributes of PSCL's in controlling material flows in that components are only moved from kanban areas when all cells are empty. and

c. to monitor the quantities of parts within different parts of the model, when validating the model.

7.4 Verification and Validation

The verification, or debugging, of the simulation program was performed at intervals during model construction. In order to identify programming problems the on/off toggle facility was used making only a small number of components active at a time.

Model elements requiring debugging were identified using the graphical animation of the simulation runs to monitor the values of specific variables and to observe the general flow of parts through the system. The trace feature was also used to monitor discrete steps of the simulation, when searching for a particular problem, e.g. to determine precedence when two events happen simultaneously.

Once the model was debugged, pilot runs of the model were carried out to ensure that the model performed as intended. Appropriate modifications were made to the program to correct errors in the model that could be seen from the observations. The information contained in the results file were examined for any unexpected results, e.g. zero results when a value was expected.

Determining whether the simulation model was an accurate representation of a real world system was a particular problem, since the PSCL model represents a hypothetical system. However, since the model was developed by the researcher, the validation requirements provided by Buffa and Sarin[169] were satisfied, i.e.:

a. decision makers were involved in modeling and validating,

b. the validator (researcher) has an insight into the nuances and mechanics of the system, and

c. the validator (researcher) was intimately involved with the system.

A detailed analysis, to identify the sensitivity of the output values to changes in the values of inputs, was not considered to be appropriate at this stage in the PSCL development process. However, since comparisons were required of models containing varying batch sizes and components variety, observations were carried out to ensure that changes to models resulted in output values that made qualitative sense in terms of their direction and magnitude of change.

Since the model is a representation of a theoretical system, no existing system data is available for comparison with the model. Observing how the components of the model operate could not, therefore, be compared with results derived analytically or manually.

7.5 Experimental Design

The objectives of the simulation exercises performed were to provide an understanding of the operational dynamics of PSCL's. At this initial stage in the development of the PSCL methodology a systematic exploration of model alternatives was not appropriate and, therefore, not attempted. Hence detailed experimental design of the simulation exercises and statistical tests to provide confidence intervals when measuring output values were not necessary.

The selection of 'batch sizes' and 'number of component types' to include in the simulation models was initially determined such as to maximise component variety (41 part types) consistent with maintaining model building time within reasonable limits. A minimum number of part types was also selected consistent with there still being sufficient variety in the system to be termed HV/LV.

7.6 Analysis and Evaluation

The results of the simulation runs were examined both visually and analytically (using ProModel report files) in order to gain insights into the dynamic workings of the PSCL system. The following results were obtained:

The content history graphs shown in Figures 11 to 16 indicate the following:

1. Cell cycle times are controlled by the bottleneck cell, i.e. materials will only move between cells once the bottleneck cell has completed its kanban quantity. Hence the time batches wait, (i.e. analogous to queueing), prior to moving to the next process is, therefore, controlled by bottleneck cells. Maximum cell cycle times range from 2.17 hours (batch size 20, part variety 41) to 3.57 hours (batch size 40, part variety 41). Hence the maximum leadtime for a batch requiring 5 operations would not exceed 5 x 3.57 which equals 17.85 hours. This is considerably less than queueing times within batch processing environments which are normally measured in 'days'.
2. As part variety increases, from 20 to 41 part types, there appears to be no causal effect on cell cycle times.
3. As batch sizes increase, as would be expected, bottleneck cell cycle times increase, i.e. 2.17 hours (batch size 20, part variety 41) increasing to 3.57 hours (batch size 40, part variety 41).
4. The model has determined kanban quantities on a random basis. This has resulted in bottleneck cycle times varying. Materials would, therefore, move at the irregular intervals dictated by the bottleneck cells. However, it could be expected that kanban signals could be used to direct continuous improvement to the problem areas effecting regularity of material movement.

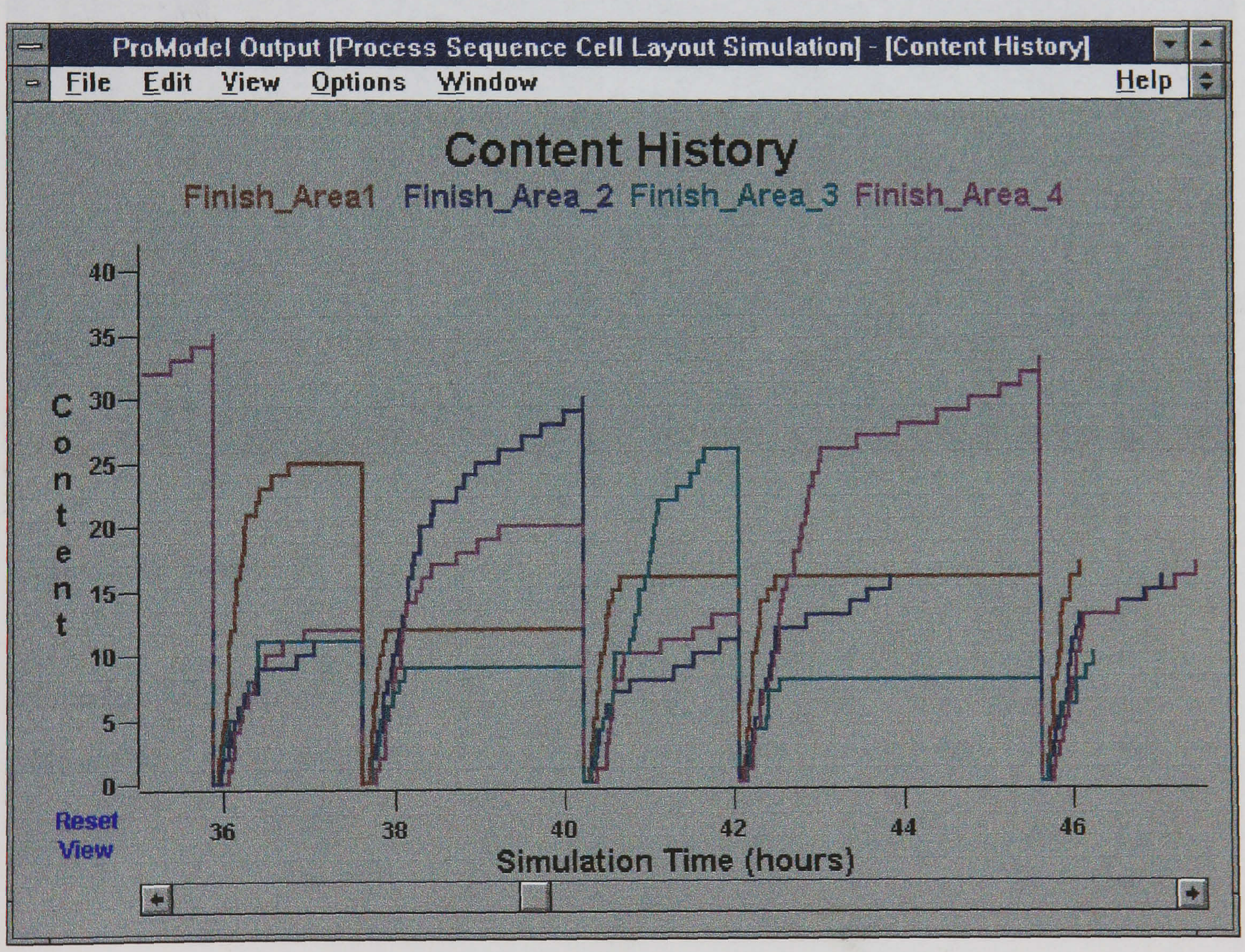
7.6.1 Achievement of Key Requirements

1. Cope with component variety - the results of the simulation has indicated that changes in level of component variety have no appreciable effect on bottleneck cycle times.

2. Visible identification of bottlenecks - since material movements are controlled by the bottleneck cell it can be assumed that empty kanban areas could be used as visible signals of cells containing bottleneck resources.
3. The simulation has been designed to cope with components requiring differing numbers of operations that can enter the system and leave at a variety of cells. This has no significant effect on material flows, since the majority of components move only in a forwards direction.

7.6.2 Model 1 Batch size 40, Part variety 41

Figure 11 - Content History (Batch Size 40, Part Variety 41)

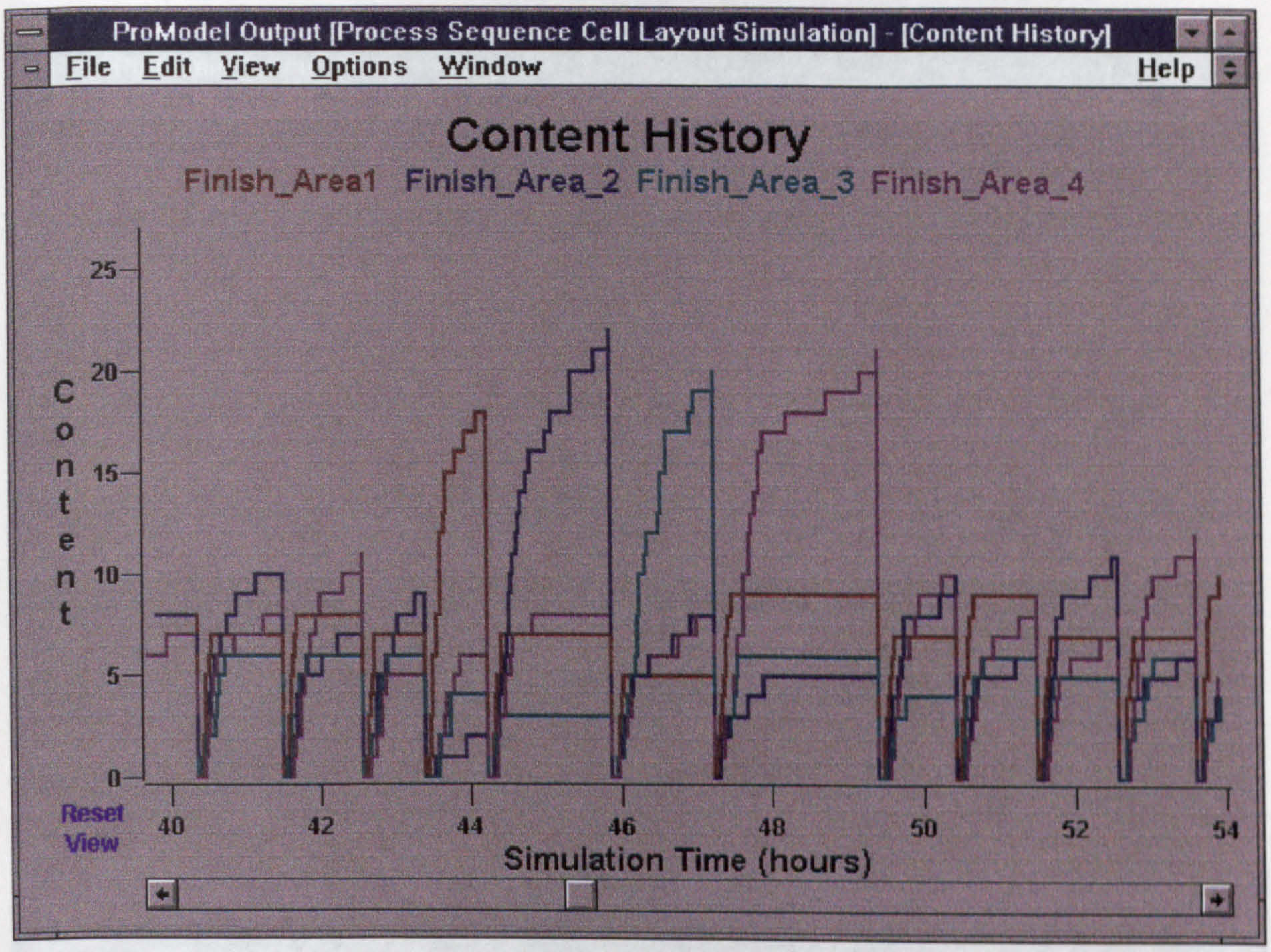


Cell Cycle Times

Minimum	1.6405 hours
Maximum	3.5753 hours
Average	2.3119 hours

7.6.3 Model 2 Batch Size 20 Part Variety 41

Figure 12 - Content History (Batch Size 20, Part Variety 41)

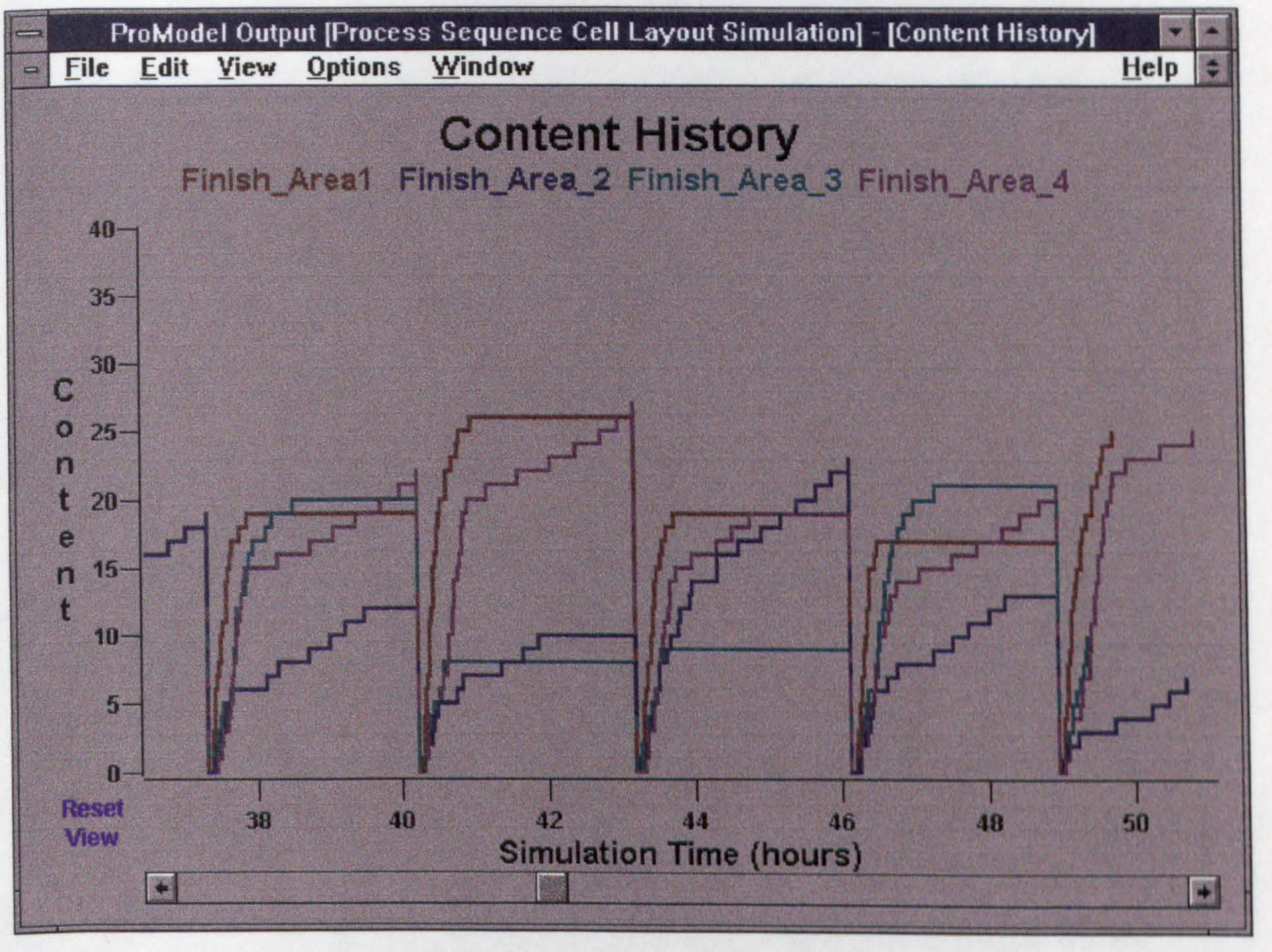


Cell Cycle Times

Minimum	0.8219
Maximum	2.1755
Average	1.2292

7.6.4 Model 3 Batch size 40 Part Variety 30

Figure 13 - Content History (Batch Size 40, Part Variety 30)

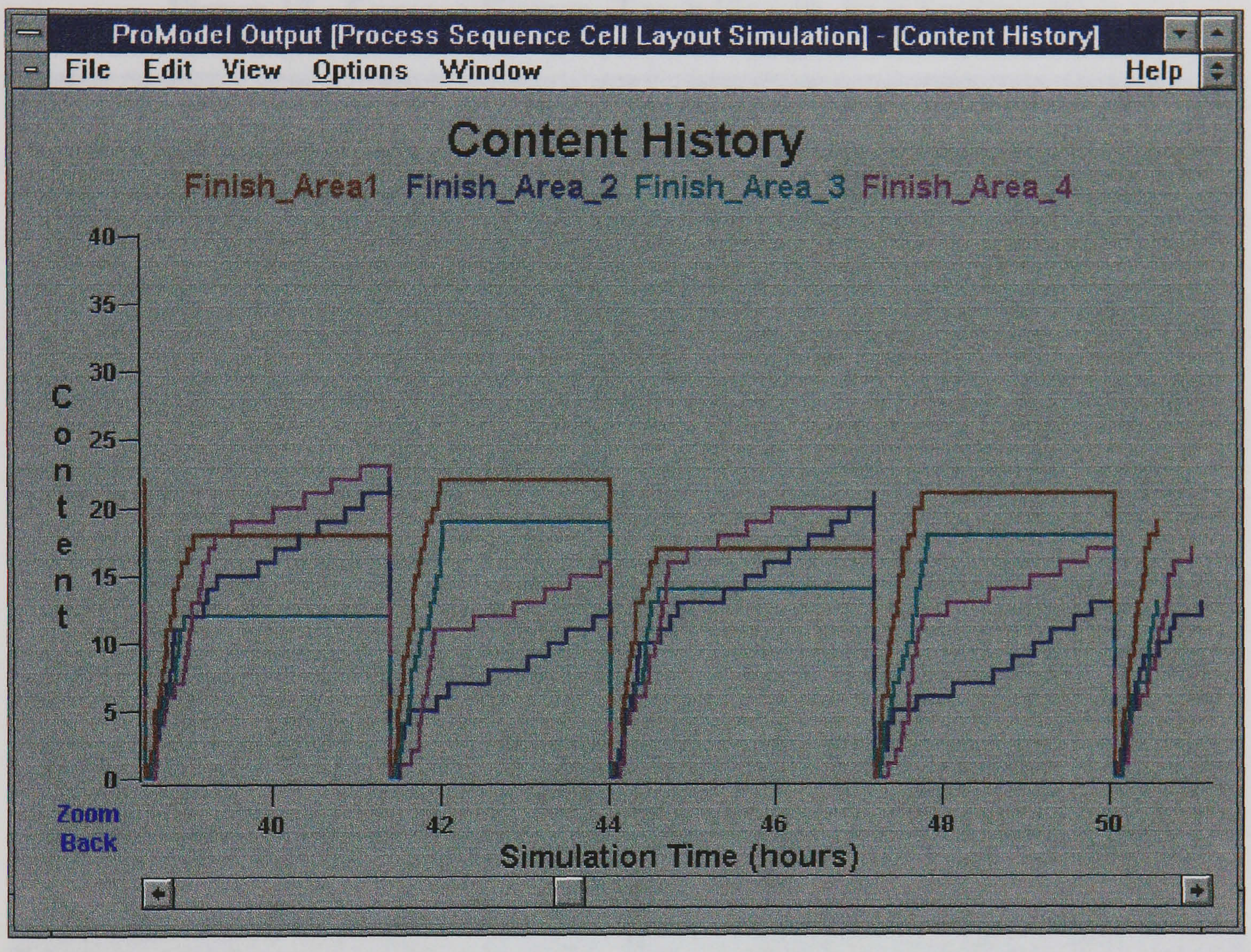


Cell Cycle Times

Minimum	0.6133
Maximum	2.1755
Average	1.2043

7.6.5 Model 4 Batch Size 40 Part Variety 20

Figure 14 - Content History (Batch Size 40, Part Variety 20)



Cell Cycle Times

Minimum 2.6349

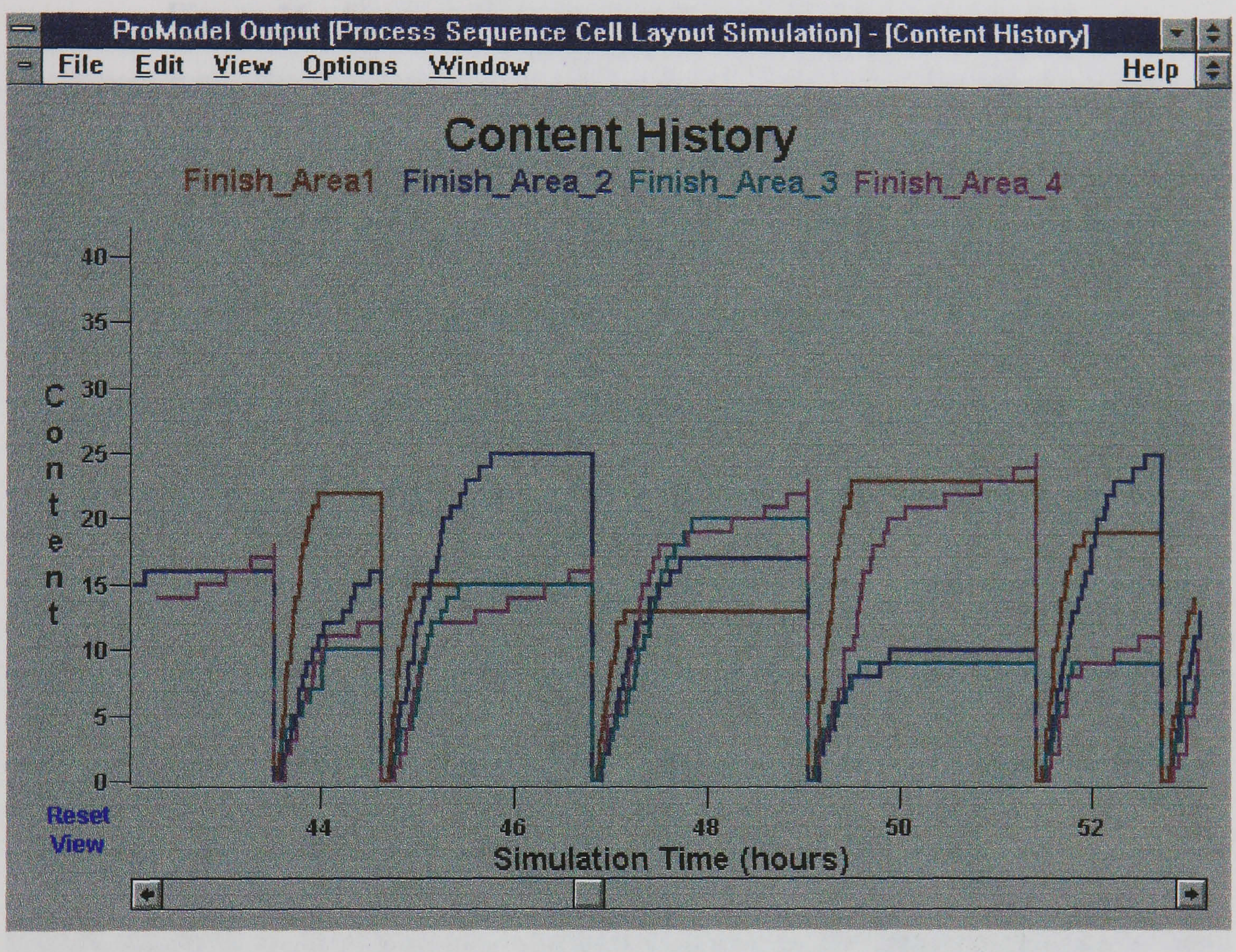
Maximum 3.2444

Average 2.8791

7.6.6 Model 5 Batch Size 40 Part Variety 41

In this model set-up times for bottleneck machines have been reduced.

Figure 15 - Content History (Batch Size 40, Part Variety 41)



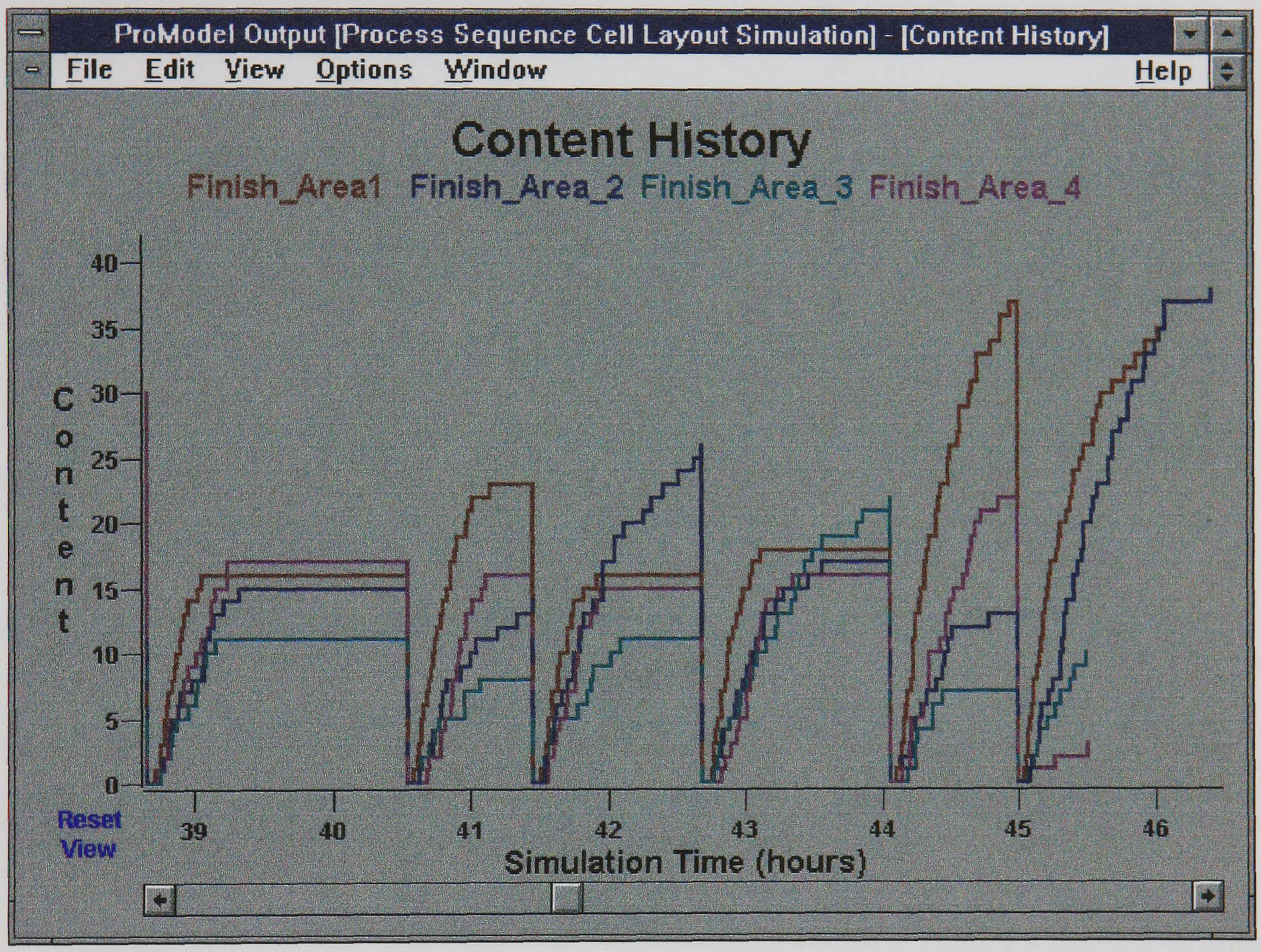
Cell Cycle Times

Minimum	1.1148
Maximum	3.6003
Average	2.1712

7.6.7 Model 6 Batch Size 40 Part Variety 41

In this model set-up times for bottleneck machines have been reduced and the problems of long processing times by Machine S have been reduced.

Figure 16 - Content History (Batch Size 40, Part Variety 41)



Cell Cycle Times

Minimum	0.9053
Maximum	2.8114
Average	1.8693

Chapter 8

8. Discussion

8.1 Introduction

The problems associated with the use of batch manufacturing techniques have been identified in Section 1.1 as difficulties in maintaining acceptable lead times, reliable delivery dates, reliable quality and minimising manufacturing costs.

The characteristics of batch manufacturing that make it difficult to improve in these problem areas have been identified as the need to adopt a functional based plant layout methodology and the complexity of the production planning and control methods that need to be employed.

The introduction of JIT techniques through the use of GT and cellular manufacture has been identified as bringing significant benefits when implemented in batch manufacturing environments. However, in HV/LV manufacturing environments the potential for using JIT techniques has been found to be limited (Section 1.3.2).

An alternative plant layout methodology (PSCL's) has been proposed (Chapter 5) that enables many of the techniques involved in JIT to be implemented within HV/LV environments. In this respect, the basic aims of introducing PSCL's are to:

a. make manufactured parts flow in one direction through the shopfloor,
b. provide a suitable environment for kanban controls to operate,
c. provide a suitable environment for continuous improvement procedures,
d. provide the basis for an integrated planning and control system that enables local control to rest with the shopfloor, and
e. provide an environment for operators to work as a team.

8.2 Plant Layout

PSCL's involve allocating items of equipment to cells according to their position within the operation route of components. Each cell, therefore, represents a stage in the processing sequence of all components manufactured within a company. Hence, the PSCL facility layout methodology has similar characteristics to those of flow lines, i.e.:

1. Each cell within a PSCL represents a stage in the process sequence of a component, hence items are manufactured or assembled as they pass through a series of cells, i.e. these cells are analogous to the production stages in traditional flow lines and materials flow in one direction. For example, Section 6.4.1 shows that 95.2% of materials would flow forwards from one cell to an adjacent cell within the PSCL. Hence this feature of PSCL's will assist in reducing material handling costs substantially when compared to functional layouts used in batch manufacture. It will also help to provide fast feedback to those operators who are responsible for producing defective items.
2. Raw materials and components can enter the system at a specific cell depending on the number of individual operations required, i.e. they can enter at certain points along the sequence of production cells. For example within the PSCL designed for RTH Ltd. (Section 6.4), parts can, depending on their processing needs, enter the system in the first four cells. Correspondingly, the model created to simulate PSCL's reflects this feature, e.g. entity V enters the system at cell 3 and leaves at cell 5, entity 14 enters the system at cell 4 and leaves at cell 5.
3. Within a PSCL, production cells should be positioned such that the maximum amount of work flows in one direction without omitting cells in the sequence, precedence constraints are not broken, sites are made available for interprocess buffer stores between adjacent cells and incomplete items cannot leave the production sequence.

One characteristic of flow lines not achieved using PSCL's is that finished components or products would not necessarily be delivered from the end of the line, i.e. the final cell. In the case of the PSCL developed using RTH Ltd. data and hence the PSCL simulation model, parts can leave the system before the final operation. For example, Entity U enters the system at Cell 1 and leaves at Cell 3, Entity 10 enters the system at Cell 2 and leaves at Cell 4. However, this problem may be resolved by placing a kanban completion area at the end of the final cell in the PSCL and using this to hold all components from whatever cell they are completed at.

When compared with the use of GT within HV/LV environments, the adoption of PSCL's have the following important advantages, i.e.:

1. GT may not be applicable due to the difficulty in identifying groups of components from which to form cells. However, within PSCL's machines are only grouped according to their positions within component route sequences and not according to common design or process features.
2. Hybrid GT systems are often utilised in which a proportion of components may not be assigned to cells. Hence, the advantages gained from using flow processing techniques are only achieved on a limited number of part types. PSCL's incorporate the whole range of manufacturing equipment and incorporate the benefits of flow manufacture due to the majority of parts proceeding in one direction through the cells.
3. GT cells often cannot fully process all the components assigned to them necessitating components leaving the cell to be processed then returned to the cell for further processing. PSCL's however fully process all parts that enter the system, whatever the variety of parts.
4. GT cells are restricted to manufacturing a limited variety and volume of parts by their design, limiting flexibility and making it relatively insensitive to the changing needs of the market. PSCL's, however, can cope effectively with changes in product mix as they are design to process a wide variety of parts.

The error prone, time consuming and high costs of processing numerical codes when designing GT cells often leads to long delays in implementing systems. When designing PSCL's the existing process routes held within computerised production control systems, such as MRP and MRPII can be downloaded into a commercial spreadsheet package saving time and data entry. Prior to entry into the spreadsheet, however, the data should be analysed by relevant personnel who are familiar with the components manufactured in order to eliminate those items that are no longer manufactured and are not likely to be manufactured again.

Results from the RTH Ltd. case study indicate that the majority of processing equipment used can be allocated to individual process cells without capacity problems arising. However, as with any type of plant layout arrangement, some capacity problems would occur, i.e. potential solutions to capacity problems that have emerged when designing GT cells are applicable during the design of PSCL's, i.e.:

a. purchasing additional items of equipment if financially justifiable,
b. amalgamating cells into larger groups,
c. flexible allocation of labour between cells, and
d. redesign of products, components and processes.

Other potential solutions have been identified that are specific to PSCL's, i.e.:

a. making equipment more mobile and moving it between cells,
b. inter-cell subcontracting of work,
c. if equipment type required in two adjacent cells then locate in either the preceding or succeeding cell, and
d. because machines are independent, if one machine breaks down then other machines are not affected as with cellular manufacture, i.e. the PSCL system will not stop due to the breakdown of a single machine.

8.3 Kanban Material Controls

In order that kanbans can be used to control material movements within PSCL environments it is necessary that:

8.3.1 The flow of materials follows a set visible path

Within PSCL's there would be a sequential movement of materials that would flow from one cell to the next cell in the processing sequence irrespective of the part type.

The potential, therefore, exists for implementing kanban controls that regulate the flow of work between adjacent cells.

8.3.2 Physical visible signals can be implemented

The type of kanban signal, (i.e. container or floor area), chosen would depend on the physical size of part types, batch sizes and the number of part types moving at any one period of time between cells. The variety of part types that need to be processed frequently results in traditional kanbans not being able to cope with such conditions. PSCL's would need to use a modified form of kanban to control material flows, that would allow a high variety of parts to be physically moved. It is proposed that these kanbans would take the form of containers that could hold a variety of different part shapes and sizes, e.g. kanban containers could take the form of multilayered racks. In this type of container each shelf would hold materials for a specific machine within the cell. A full layer would act as a visible signal not to produce any more items for a specific machine.

The specific function of the kanban signal would be to signal when more materials needed to be produced for specific machines within the next cell in the process sequence. In this respect, because of the irregular nature of the demand for part types, kanban signals would be limited to controlling when materials could be moved and would not directly signal which part needed making. Materials would only be allowed into the system upon receipt of a kanban signal that more materials for a specific machine were required.

8.3.3 Physical prevention of the build-up of work-in-progress is possible

Implementing container based kanbans would physically limit work-in-progress levels by controlling the number of sites in which to place materials. Excess work-in-progress would be avoided by using standard containers and restricting the number of containers allowed into the system. Containers would also make the build-up of inventory highly visible. Restricting the number of containers or sites where containers may be stored provides a physical limitation to the build-up of excess inventory. Removing some of the available containers from the system physically prevents the production of work-in-progress.

8.3.4 Reduced handling requirements are achieved

The use of containers that hold a variety of part types will help to minimise container movements. In addition, using kanban container areas near to processing cells would again reduce handling. As improvements were made it would be expected that the frequency with which containers were moved would increase. Hence, additional involvement would be required by cell operators in handling materials in order to prevent increases in indirect handling costs.

8.3.5 Disciplined material control procedures to be achieved

Within PSCL's, as in traditional JIT systems, achieving disciplined working procedures would require well documented manufacturing procedures and well trained workers who are well motivated towards following them.

8.3.6 The PSCL is robust when coping with change.

Here PSCL kanban systems must be capable of coping with the variety of changes that take place at the shopfloor level, in this respect a kanban control system has been incorporated into the simulation model (Chapter 6) and the results indicate that changes in the variety of components and processing batch sizes has a negligible effect upon the operation of the entire system. In practice, fluctuations in demand would need to be handled by adding or removing kanban containers.

An effective kanban system must also assist in focusing continuous improvement activities. Within a PSCL, as in traditional JIT systems, kanban movements would enable disruptions to material flows through the system to be identified. Continuous improvement efforts, could, therefore, be focused by forced reductions in the number of containers in the system or the amount of WIP in the individual containers.

Kanban controls must be established such that bottlenecks are provided with sufficient buffer stocks to ensure that they can operate continuously. The entire PSCL system actually acts as a physical OPT system as it is impossible to utilise non bottleneck resources to manufacture parts that are not required.

8.4 Cell Cycle Times

The use of PSCL's makes possible the use of the concept of cell cycle times for:

a. controlling the flow of work through the system, and
b. planning purposes, e.g. MRP lead time phasing.

Within traditional JIT cells and flow lines, cycle times would be time buckets allocated to the equipment within the cells for the completion of all materials moved as a result of a kanban signal. Similarly in PSCL environments, cycle times would be based on the time taken to process and transfer one kanban quantity of parts from one cell to the next cell in the process sequence.

Within an individual cycle time period, a cell would need to process the components from each cell's kanban area, i.e. a kanban area could hold several containers. Cell operators and supervisors would need to schedule this work within the cell such that lead time constraints were not exceeded, i.e. delays in the flow of work through the system did not occur. Responsibility and authority for scheduling work within the cell would, therefore, be allocated to cell personnel.

In traditional flow systems line balancing takes place, i.e. each work station is allocated similar amounts of work and all work stations are then allocated a cycle time in which to complete their work allocation. The work then flows from one work station to the next at the end of each cycle time. In a PSCL, the cycle times are specific to each cell and will depend on the amount of work in the kanban containers.

In traditional balanced JIT flowlines equal amounts of work can be allocated to individual workcentres. In a PSCL, the simulations (Chapter 6) show that cells would be allocated unequal amounts of work hence irregular work flows would result.

However, the model has been constructed to move materials using kanban control. Kanban movement is only initiated when all cells have completed their allocation of work. Work flow is, therefore, irregular because it is impossible to give different cells an amount of work that would take the same time to process.

In a traditional flowline, the rate at which work flows is effectively controlled by the bottleneck resource. This is also the case in PSCL's since containers will remain full at non-bottlenecks until the materials being processed at the bottleneck resource are completed and moved along the sequence.

In order to regulate cycle times sophisticated scheduling techniques would be required that could balance cell work loads as materials moved through the sequence. Such scheduling techniques would be a disadvantage since it would upset the natural order in which jobs need to be processed as determined by the MRP system.

The concept of having cell cycle times has advantages, i.e.:

1. Cell cycle times are controlled by the amount of work that represented one kanban signal.
2. Forced removal of batches would not result in more set-ups but simply reduce cell cycle times.
3. Bottlenecks within a PSCL could be easily identified as shown in the simulation (Chapter 6) i.e. longer cycle times would result at the cell containing the bottleneck. The irregular flow of kanban containers that would then take place could be used to identify such hold-ups. In this way work-in-progress would be directly linked to manufacturing lead times. The bottlenecks identified in this way would be those that directly influenced overall manufacturing lead times.
4. Provide a focus for leveling work loads between cells, as major discrepancies would be highlighted in the cell that contained the bottleneck.
5. Improvements can be forced by the reduction of cell cycle times rather than the removal of individual kanban signals from the system. Continuous improvement

could be directed at both reducing cycle times and balancing work contents as with a traditional flow line.

6. Bottlenecks could be used to focus set-up reduction activities. Reductions in the processing batch sizes will result in more frequent set-up operations being required. Hence, set-up times will begin to reduce the available processing time within a cell. In a PSCL environment problems with long set-up times will present themselves as an inability of a cell to maintain its lead time cycle. Only the set-up operations having a direct effect on manufacturing lead times could be identified and made the subject of continuous improvement exercises.
7. The overall lead time for completion of an individual component through the entire system would be the sum of the cycle times for the individual cells that the component is processed at. In this way overall lead times for components could be used for MRP time phasing of works orders and hence the release dates of works orders onto the shopfloor.
8. A major role of the design department is to support a JIT environment by redesigning components in order to improve their manufacturability. Since each cell will represent a known part of the overall manufacturing lead time for components the effect of the following design improvements will be directly visible, i.e.:

a. removal of processing operations,
b. redesign of those components that require bottleneck resources,
c. reducing the number of components within an assembly or product,
d. ensuring that the quality of an item can be easily measured,
e. reducing the number of set-ups required by using common components within different products,
f. redesign components to avoid difficulties during manufacture and to minimise the possibility of defective items being produced,
g. reducing the length of set-ups by designing parts to use common tooling,
h. improving quality by reducing processing and design complexity, and
i. improving quality by reducing the numbers of unique parts, i.e. parts become more familiar with a reduction in number of part types.

9. The simulation clearly identifies the effect of the bottleneck cell on the system in that capacity is available at non-bottleneck cells. This can reduce the level of capacity planning detail required to ensure that individual items of equipment within cells are not over-loaded during any cell cycle time. The detail involved in this planning would depend on how clearly bottleneck resources could be identified.
10. Shorter cycle times in PSCL's leads to an improvement in quality through the faster feedback of quantity information from succeeding cells.

8.5 Role of MRP

Integrated MRP/kanban planning and control tools are now established practice at a number of organisations and these procedures would be required within a PSCL environment because of the variety of items being processed and the irregularity of component purchase lead times, order quantities and demand patterns.
Within a PSCL environment:

1. The planned order release schedules of a MRP system would determine when materials should be entered into the PSCL system using procedures described in Section 3.6.
2. Material movement would then be controlled using kanban signals, i.e. the MRP system would ensure that the correct materials and components were being 'pushed' through successive cells and by limiting the number of containers the kanban system would prevent excess work-in-progress building up.

The basic tasks, therefore, required of a MRP system would be to convert master production schedules into works order schedules and plan purchase orders such that long lead time items are available when required.

A kanban control system used in conjunction with a MRP system would improve the level of certainty within a manufacturing system by regulating the flow of materials.

Management could, therefore, be confident that once entered into the system, materials will eventually leave as completed items. No expediting would therefore be required between the stages of production, i.e. the need for shopfloor control and production schedules is avoided and booking jobs into and out of individual processes need not take place. A large number of paperwork data transactions, a major source of inventory inaccuracies, could, therefore, be avoided.

8.6 Cell Infrastructure

Within an individual cell the environment could exist for the use of cross functional teamwork. In this respect individual cells within the PSCL should provide an environment that contains total flexibility in working practices and flexibility between jobs, single status for all employees, empowered operators who feel able to take part in the improvements that take place and a strategic vision that is communicated to the workforce. An environment where the need for continual change is understood and where individuals understand that improvements provide benefits and security for themselves.

Each cell within the PSCL requires a cell team consisting of:

a. cell supervisor, and
b. cell operators, the number of which would fluctuates depending on processing capacity required.

8.6.1 Supervisor Tasks

Supervisors must have responsibility for:

1. Quality functions - Establishing systems of process control at each work station. Ensuring that the quality is measured as parts are processed and quality problems are visible by using simple control charts to monitor quality levels and record the company's quality progress, thereby maintaining quality standards and specifications.

2. Set-up functions - Operating a set-up reduction infrastructure to identify which set-up to tackle and co-ordinating cell personnel such that efficient set-up procedures can be performed.
3. Maintenance functions - Scheduling repairs and replacements to occur when processing equipment is idle whenever possible.
4. Communication functions - Communicating cell performance to management, in terms of achieving leadtime targets, quality levels and commending the performance of the team or individual team members. In conjunction with other cell supervisors planning manpower levels in individual cells. Facilitating communication between operators within the cell. Recognising and rewarding cycle time and inventory reduction efforts.
5. Continuous improvement functions - Initially by establishing a culture within the cell that welcomes problems, does not attempt to hide or cover up problems and encourages cell personnel to admit problems and work towards achieving solutions to them. Instituting and motivating focused continuous improvement programs and underpinning these with a total quality program that trains the entire cell team in the philosophy and tools of total quality control. Facilitating the identification of problems, establishing priorities for solving problems and initiating continuous improvement exercises to solve problems. It is also important for the supervisor to generate their own ideas for improvement, achieve consensus amongst team members and evaluate and monitor the results of improvements. Ensuring that the cell maintains its focus on reducing inventory and waste by utilising visual methods such as checksheets, Pareto diagrams and cause & effect diagrams for identifying problems and establishing the causes of such problems.
6. Standardising functions - Identifying the key processes within the cell, identifying who is the best at performing these practices, finding out how they achieve the best practice and from this developing informative standard working procedures. Developing standard procedures for all work activities undertaken, e.g. processing, quality control, maintenance and servicing. Standardising new improved methods with documentation which should then act as a reference for training and further improvements.

8.6.2 Operator Tasks

Operators must have responsibility for:

1. Measuring quality, collecting quality data and identifying defect causes by analysing the data collected.
2. Correcting their own quality defects.
3. Stopping the process if the process goes out of control and quality standards are not being achieved.
4. Working in clean, well maintained environments, by employing good housekeeping procedures, to promote better working practices, improve productivity and reduce the level of industrial accidents.
5. Employing preventive maintenance techniques to enable machines to be checked regularly.

In order that operators can perform such tasks the following skills are required, i.e.:

1. Operators are multiskilled and can, therefore operate other equipment in the cell. In addition opportunities exist for operators to gain multi-skills through the operation of the range of processing equipment that each cell will contain.
2. Intercell skills ensuring flexibility throughout the system.
3. A greater knowledge of the consequences of producing poor quality items.
4. A greater awareness of the causes of poor quality items.

8.6.3 Cell Team

All personnel within each cell must work as part of committed teams, use their skills to improve processes, use their initiative to identify problems and seek solutions, never settle for the status quo, continually strive to improve their work, and be willing to contribute the maximum to the benefit of the business. Within an individual cell its operators and supervisor as a cell team are given the responsibility and authority for all internal tasks such as:

1. Quality functions - Preventing poor quality through effective use of quality control procedures. Developing effective working methods that make it difficult for a defective part to be produced. Ensuring that the processing equipment used makes it easy to produce good parts and that quality specifications are within the 'process capability' of equipment. This is aided by ensuring that all personnel look on the next process as a customer.
2. Set-up functions - Planning and scheduling the components arriving in the cell in order to limit set-ups.
3. Maintenance functions - Encouraging the promotion of PM through autonomous small group activities, involving all cell operators. Providing an environment where everyone manages their own area of responsibility.
4. Communication functions - Providing effective communications by using visual aids, sharing information and holding regular improvement meetings. Supporting and recognising both group and individual efforts.
5. Continuous improvement functions - Promoting teamwork by creating an environment for problem solving, i.e. encouraging interest in the work being carried out through ownership. Developing a continuous program which concentrates on reducing cell cycle times and attacking the problems that arise as a result of these reductions. Creating an environment in which all personnel within the company expect improvement changes to take place.

8.6.4 Rewards and Performance Measurements

Reward systems should be cell based, i.e. they must:

a. guide and support the cycle of improvement,
b. emphasise improvements by rewarding individuals and groups with monetary and non-monetary rewards,
c. focus on improving shopfloor problems, e.g. quality, costs, delivery and safety, and
d. promote cooperation, within cells and between cells.

Performance measurements should also be cell based and bring about a greater degree of motivation towards finding and permanently correcting the causes of poor quality, i.e. since repetitions of problems would be more frequently reported, shop floor personnel must be motivated towards finding long-term solutions. Measurements should allow targets to be set and use visible indicators within cells to allow operators to easily see improvements in performance.

Such performance measurements would include both quality and rate based indicators and need to include:

a. internal cell cycle times,
b. manufacturing lead times,
c. number of defective parts, and
d. percentage return on sales.

Performance measurements would need to be taken after every cell cycle is completed to ensure they are timely accurate and consistent.

8.6.5 Benefits

The use of cell teams controlled by a single supervisor will provide the following benefits:

1. Allow production of small batches and hence reduce work-in-progress levels by eliminating and improving set-up procedures.
2. Allow responsibility, or 'ownership', for a production stage to rest with one group of operators and their supervisor.
3. Improve communication.
4. The variety of components that need to be processed would not need to be reduced.
5. Allow greater standardisation of processing procedures.
6. Utilise the flexibility and multiskills of operators due to machines being closer together. For example, during periods of low demand one employee may be

sufficient to operate the cell. As demand then increases, extra employees may be added to ensure that the cell can cope with the extra demand.

7. Focus on quality by reducing the time for discovery of faults.
8. Remove the need for repetitive scheduling, i.e. using a set production schedule that is repeated each production period, would not be necessary.

Chapter 9

9. Conclusions

Process sequence cell layouts have been proposed as a method of arranging processing equipment, within high variety/low volume manufacturing environments, that could assist in improving delivery reliability, manufacturing lead times and reduce quality and manufacturing costs.

PSCL's are primarily a method of laying out processing equipment and are composed of individual cells each of which contains a number of items of processing equipment. Each cell represents an individual stage in the processing routes of all components processed within a manufacturing area or company. Processing equipment is allocated to an individual cell depending on the cell's position within the operation route of components.

A procedure for identifying process sequence cells has been proposed (Chapter 6), although this research has not attempted to optimise PSCL design. This procedure was applied to a HV/LV manufacturing organisation and resulted in a PSCL design in which 95% of materials flowed in a forwards direction. One of the main elements of a PSCL is therefore, that material flows are simplified and process orientated.

A simulation model has been developed in order to understand the dynamic characteristics of material flow through a PSCL. The simulation and static analysis have enabled the benefits of PSCL's to be identified as such:

1. Materials may be controlled using kanbans. Whilst it is recognised that individual kanban containers would need to contain a variety of part types, the actual form of such containers needs to be established.
2. Although MRP would be used to generate works order schedules for components, the kanban system, in order to control WIP, would determine when batches entered the shopfloor. It could also be expected that many of the problems with providing the MRP system with accurate shopfloor data could be resolved since there would

be no requirement for expediting work and backflushing would be used to update MRP records once processing was fully completed.

3. Component leadtimes would be determined by the cycle times allocated to the cells for the completion of the kanban quantities. Either reducing kanban quantities or leadtimes would eventually lead to disruptions in material flows and hence provide direction for continuous improvement activities. Hence leading to overall reductions in manufacturing leadtimes and improving delivery reliability.
4. Bottleneck resources can be easily identified and hence their maximum utilisation can be given priority. However, it has not been identified that all short term capacity problems may be resolved.
5. An organisational structure would be provided that favoured the use of multi-skilled teams and operator responsibility for quality and lead time reductions, hence assisting in the reduction in direct overhead costs.

Chapter 10

10. Future Work

The initial research identified certain generic problems involved in designing and implementing PSCL's. The further development of PSCL's should therefore concentrate on these areas i.e.:

1. **Static design** - the static design rules specified in Chapter 5 of the report have resulted in an overall forward material flow of approximately 95%. Future work could investigate whether this figure could be improved through the use of improved design techniques to achieve improved placement of machines within cells.
2. **Kanban Controls** - Greater knowledge is also required in the area of using kanban controls in a PSCL environment in which work is essentially 'pushed' to the next processing area rather than 'pulled' as in a traditional kanban environment. Although successfully used in higher volume environments the use of 'push' kanbans in high variety/low volume environments needs closer investigation particularly with respect to controlling and reducing work-in-progress levels and reducing handling costs. In a high variety low volume environment it is essential that critical components and manufacturing resources are identified and scheduled, the use of kanban controls to perform this task also needs investigating.
3. **MRP/Kanban Integration** - Because of the part variety and length of purchasing leadtimes, MRP would be required to generate schedules of both works and purchase orders and would, therefore, be responsible for loading work into the system. Kanban signals would prevent the introduction of too much work-in-progress and control the movement of work between the cells. Research, therefore, needs to be carried out to identify the basic principles involved in integrating MRP and kanbans in this manner. For example, areas involved would include the frequency with which MRP processing is performed and the problems that arise when reducing cell lead times.
4. **Capacity Planning** - Cells would be designed using annual capacity requirements, hence long term capacity planning would be taken into consideration. However, identifying and resolving the short term capacity planning and control problems, (i.e. finite capacity scheduling), involved in such layouts would be necessary. In order to force problems to surface, (hence operate a cycle of continuous improvement

exercises), it has been proposed that reductions in cell lead times be the driving force. Again the capacity planning problems arising from such changes would need to be identified and resolved.

Chapter 11

11. List of Publications

This research has resulted in 4 journal publications and 5 conference publications. One journal publication is to be reprinted by the Open University for use in their forthcoming course "PT61: Structure and Design of Manufacturing Systems." The publications are listed below:

Stockton, D J; Lindley R J (1995): Implementing Kanbans within High Variety/Low Volume manufacturing Environments. International Journal of Operations and Production Management. 15/7, pp 47 - 59.

Stockton, D J; Lindley R J (1994): JIT for High Variety / Low Volume Manufacturing. BPICS Control, Oct/Nov, pp 31 - 34.

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Chapter 12

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